Relativistic Magnetic Reconnection Overview

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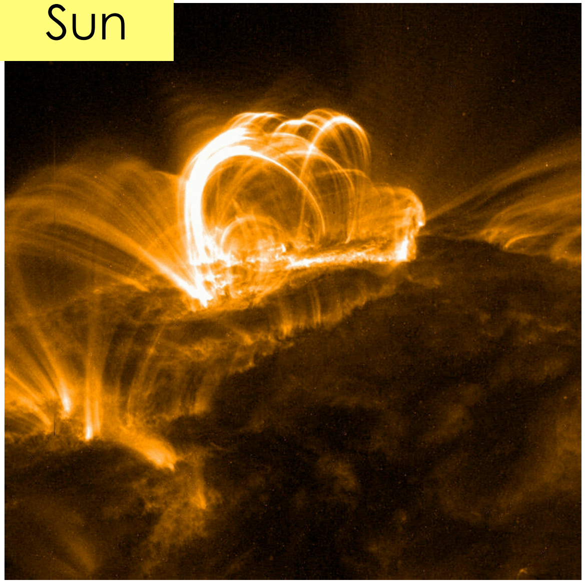
Outline

- 0. Tutorial & Introduction
- 1. MHD results
  - RRMHD simulations
  - Two-fluid simulations
- 2. Kinetic results
  - 2D reconnection
  - Another 2D instability: Drift-Kink instability
  - 3D evolution
  - Weibel instability
- 3. Summary

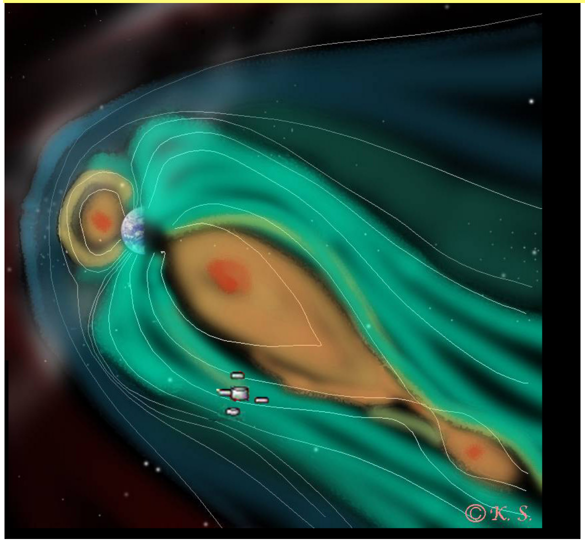
0. Tutorial & Introduction

Magnetic reconnection

Sun

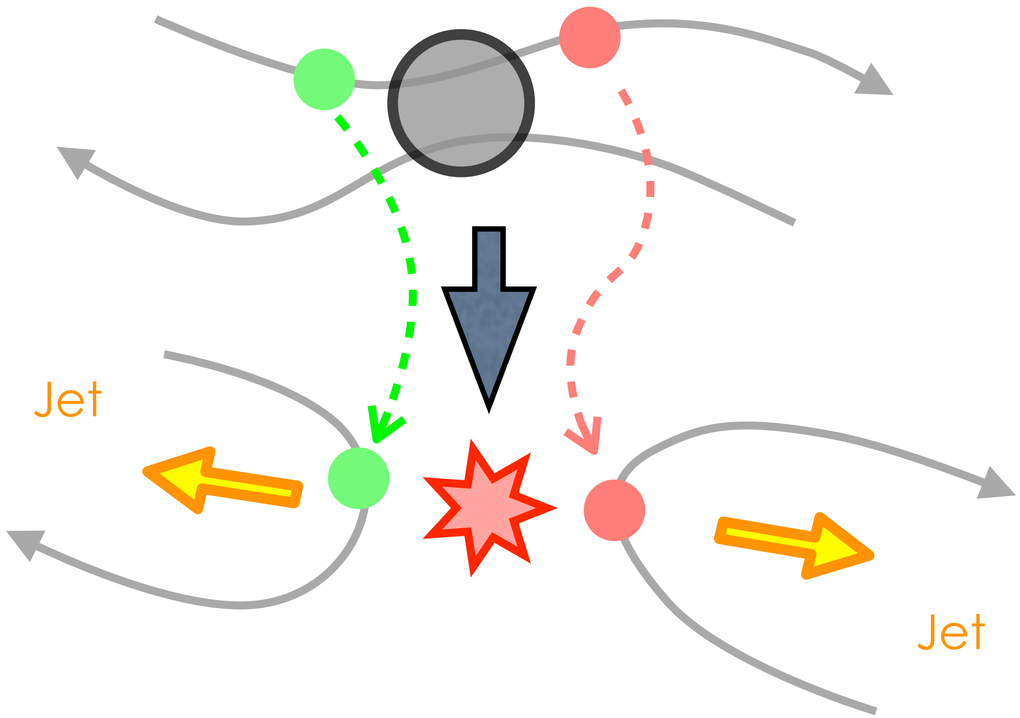


Earth's Magnetosphere

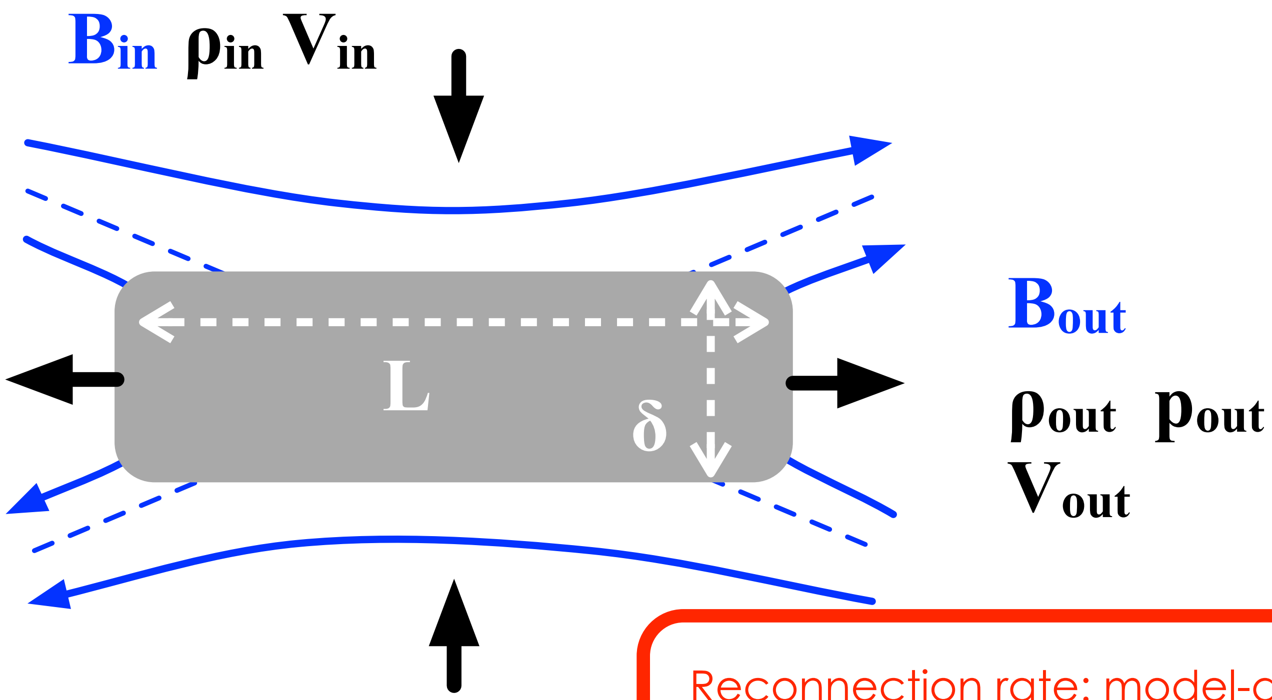


- MHD-scale phenomena
- Re-configuration of magnetic field lines
- Release of magnetic energy to plasma energy

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} \neq 0$$



Basics properties in RX



Energy conservation

$$\frac{B_{in}^2}{4\pi} L v_{in} \sim \left(\rho_{out} v_{out}^2\right) \delta v_{out}$$

Continuity

$$\rho_{in} L v_{in} = \rho_{out} \delta v_{out}$$

Reconnection rate: model-dependent

~ Mach number of V_{in}

~ Energy transfer rate

$$R \sim V_{in} / c_{A,in}$$

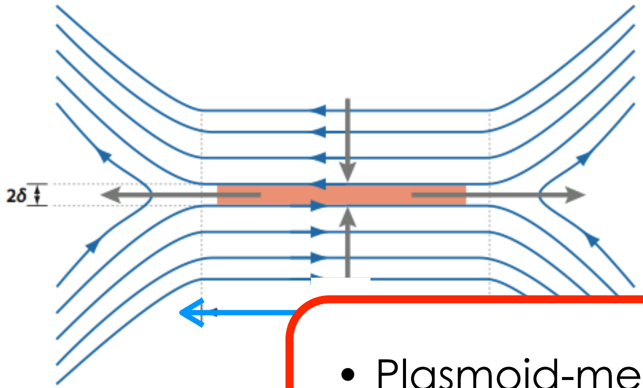
Outflow speed ~ Alfvén speed

$$\frac{B_{in}^2}{4\pi \rho_{in}} \sim v_{out}^2 \qquad V_{out} \sim c_{A,in}$$

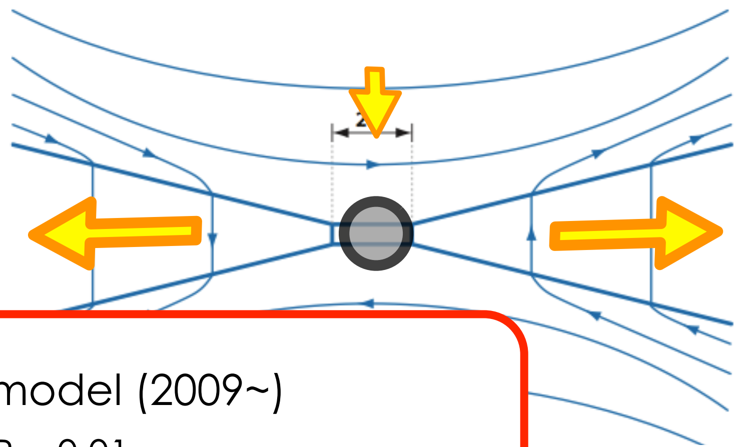
MHD reconnection models

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

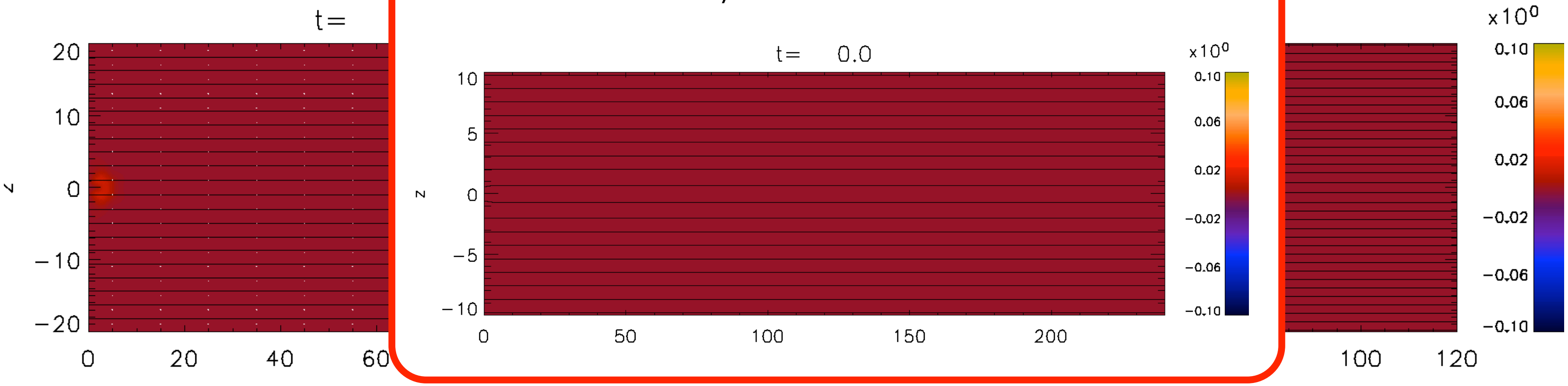
- Sweet-Parker (SP) model (1958,1957)
    - Slow : R ~ (η/L)**0.5



- Petschek (PK) model (1964)
    - Fast : R ~ 0.1

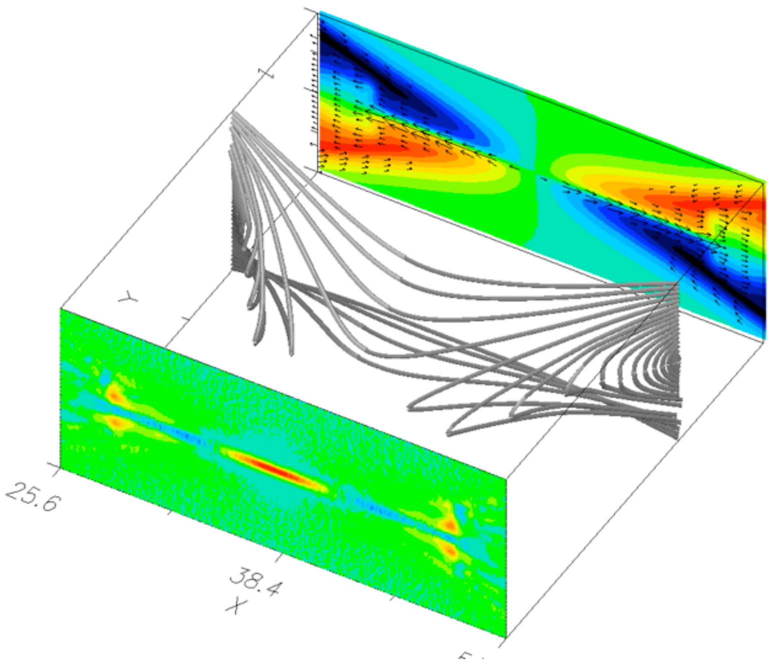


- Plasmoid-mediated model (2009~)
    - Moderately fast : R ~ 0.01

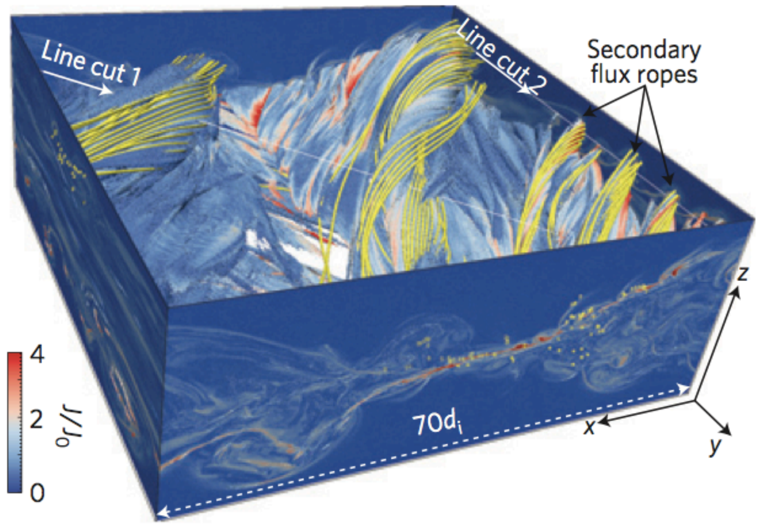


Kinetic reconnection

- Collisionless reconnection is fast: R ~ 0.1
- It looks different from MHD fast (Petschek) reconnection
- What makes reconnection fast?
    - Electron dynamics (Hesse+ 1999) vs Hall effects (Mandt+ 1994)

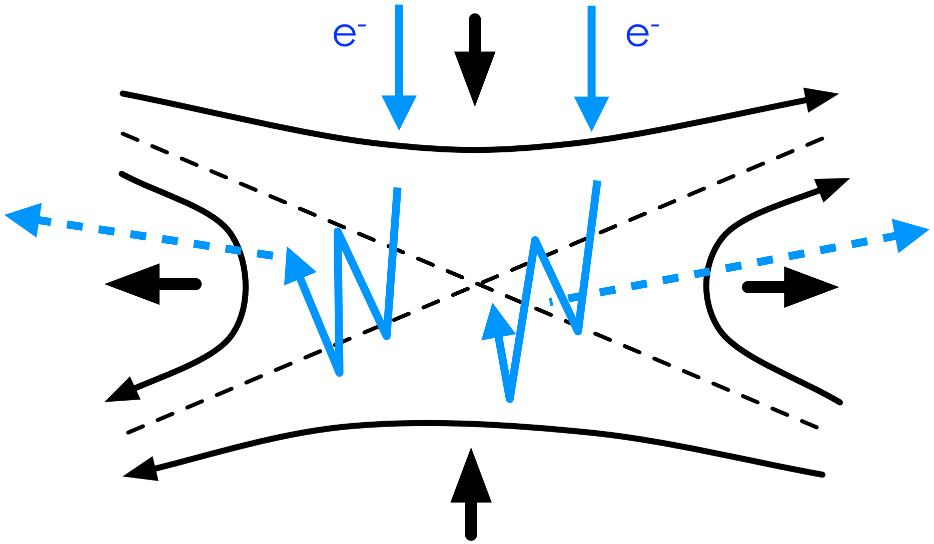


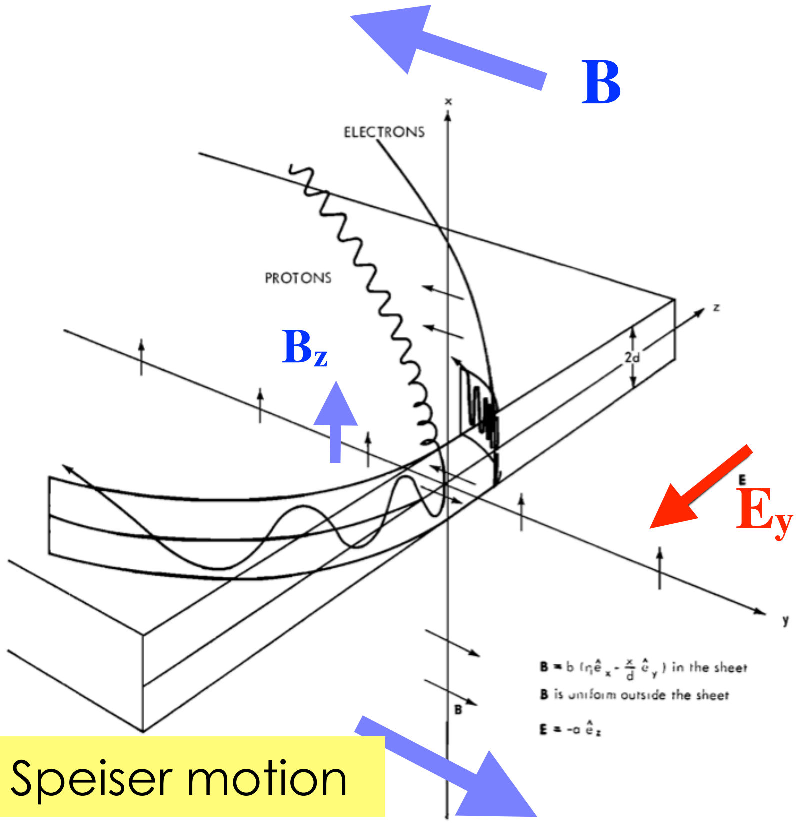
Zenitani 2011 PoP



Daughton+ 2011 Nature Phys.

Particle motion around the RX site



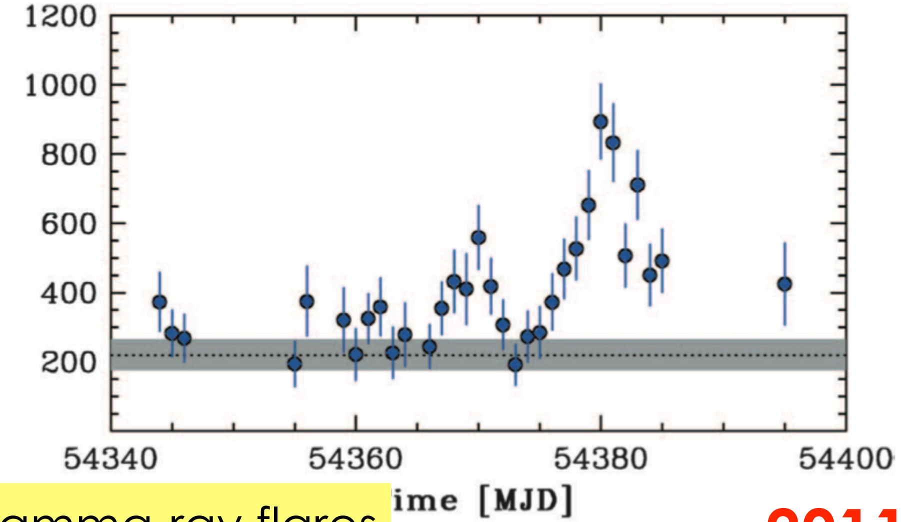


Speiser 1965 JGR

No fluid closure for electron/ion/MHD fluids

Magnetic reconnection in relativistic astrophysical settings

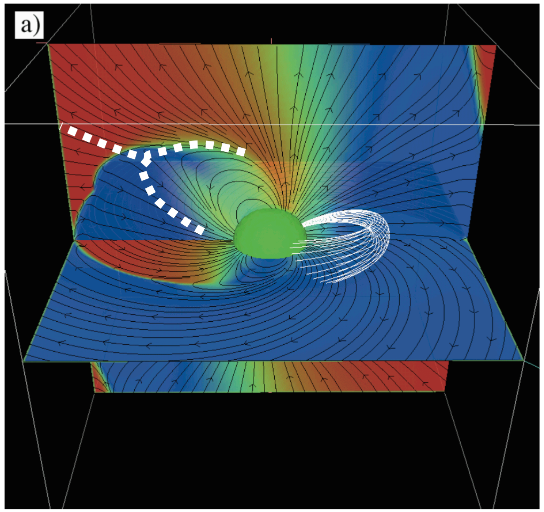
- Electron-positron pairs (and few baryons)
- Strong magnetic fields
- Relativity plays a role
  - + radiation, pair creation …



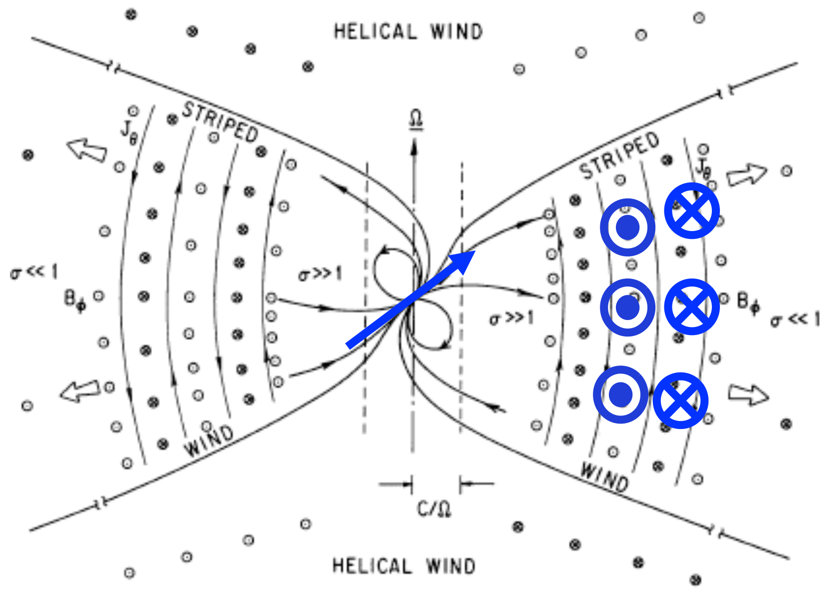
Gamma-ray flares

Tavani **2011**

Magnetosphere model



Spitkovsky 2006



Striped wind

Coroniti 1990

Current status of relativistic reconnection research (2014Q1)

- Theories have been discussed over decades
- Many works came out after 2011 (Crab flare)

MHD theories

Blackman & Field 1994

Lyutikov & Uzdensky 2003

Lyubarsky 2005

Tenbarge+ 2010

Comisso & Asenjo 2014

- Basic properties are under debate

MHD simulations

Watanabe & Yokoyama 2006
Zenitani+ 2010
Takahashi+ 2011
Mizuno 2013
Takamoto 2013
Baty+ 2013

- Ideal for global modeling

Two-fluid simulations

Zenitani+ 2009

- Meso-scale evolution

Kinetic (PIC) simulations

Zenitani & Hoshino 2001-2008
Jaroschek+ 2004
Jaroschek & Hoshino 2009

Liu+ 2011
Sironi & Spitkovsky 2011, 2014
Cerutti+ 2012-2014
Kagan+ 2013

- Fast evolution
- Particle acceleration

1. Fluid simulations

Resistive Relativistic MHD (RRMHD) eqs.

Continuity

Energy & Momentum

$$(\rho U^{\mu})_{,\mu} = 0, \qquad (T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{\rm em})_{,\mu} = 0$$

Maxwell eqs.

$$F^{\mu\nu}_{,\mu} = -J^{\nu}, \qquad F^{*\mu\nu}_{,\mu} = 0$$

Ohm's law

$$F^{\mu\nu} u_{\nu} = \eta \Big(J^{\mu} + (J^{\nu} u_{\nu}) u^{\mu} \Big)$$

Resistive Relativistic MHD (RRMHD) eqs.

Watanabe & Yokoyama 2006, Komissarov 2007

Continuity

$$\partial_t(\gamma\rho) + \nabla\cdot(\rho\boldsymbol{u}) = 0$$

Momentum

$$\partial_t(\boldsymbol{m} + \boldsymbol{E}\times\boldsymbol{B}) + \nabla\cdot\Big((p + \frac{B^2+E^2}{2})\boldsymbol{I} + w\boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} - \boldsymbol{E}\boldsymbol{E}\Big) = 0$$

Energy

$$\partial_t(\mathcal{E} + \frac{B^2+E^2}{2}) + \nabla\cdot(\boldsymbol{m} + \boldsymbol{E}\times\boldsymbol{B}) = 0$$

Maxwell eqs.

$$\partial_t\boldsymbol{B} + \nabla\times\boldsymbol{E} + \nabla\psi = 0$$

$$\partial_t\boldsymbol{E} - \nabla\times\boldsymbol{B} + \nabla\phi = -\boldsymbol{j}$$

Virtual potentials to fix div B, E (Munz '00, Dedner '02)

$$\partial_t\psi + \nabla\cdot\boldsymbol{B} = -\kappa\psi$$

$$\partial_t\phi + (\nabla\cdot\boldsymbol{E} - \rho_c) = -\kappa\phi$$

Charge conservation

$$\partial_t\rho_c + \nabla\cdot\boldsymbol{j} = 0$$

Ohm's law

$$\gamma\Big(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} - (\boldsymbol{E}\cdot\boldsymbol{v})\boldsymbol{v}\Big) = \eta(\boldsymbol{j} - \rho_c\boldsymbol{v})$$

four velocity	momentum	energy	enthalpy
$\boldsymbol{u} = \gamma\boldsymbol{v}$	$\boldsymbol{m} = \gamma w\boldsymbol{u}$	$\mathcal{E} = \gamma^2 w - p$	$w = \rho + 4p$

Relativistic Petschek reconnection

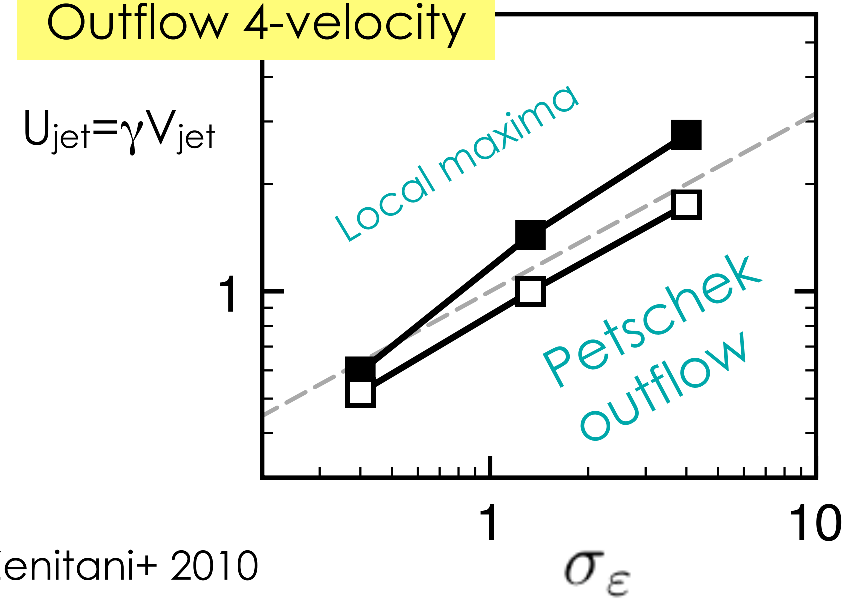
- Magnetization parameter

$$\sigma_\varepsilon = \frac{B_0^2}{4\pi\gamma^2 w} \left(\approx \frac{8}{5} \frac{\mathcal{E}_{EM}}{\mathcal{E}_{fluid}} \right)$$

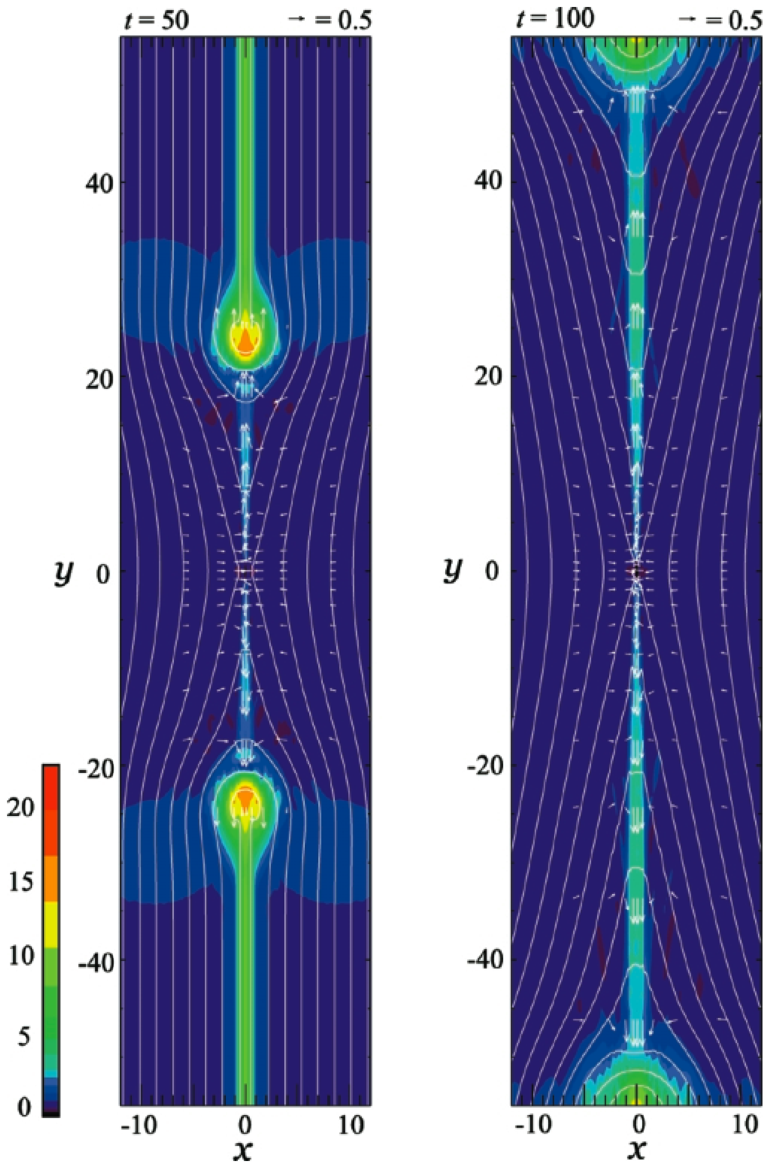
- Relativistic Alfvén speed

$$\gamma_{jet} v_{jet} \approx \gamma_A c_A = \sqrt{\sigma_\varepsilon}$$

Outflow 4-velocity



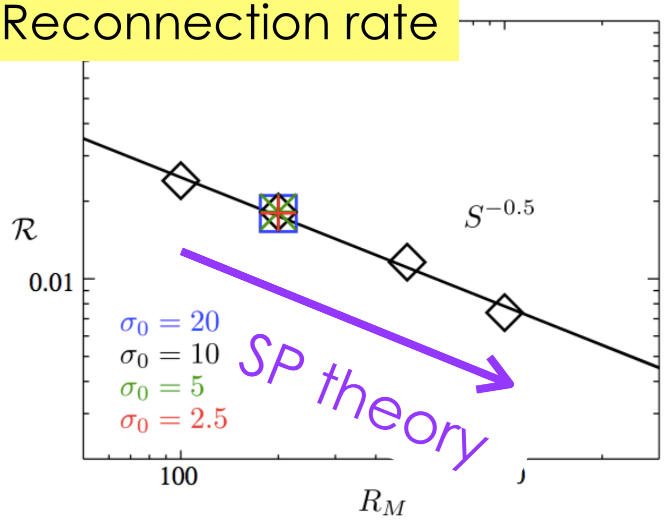
Zenitani+ 2010

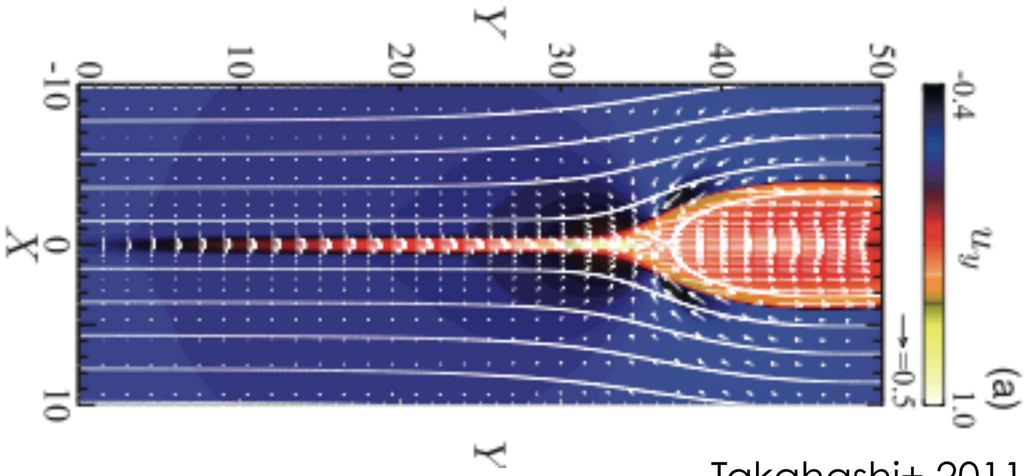


Watanabe & Yokoyama 2006

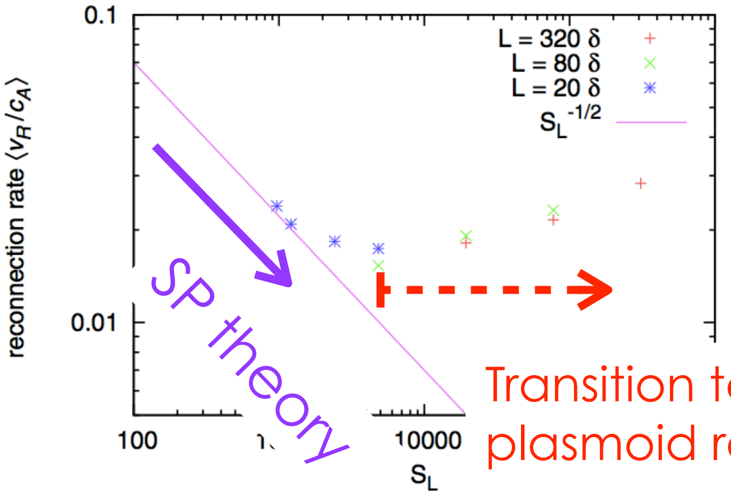
Relativistic Sweet-Parker reconnection

Reconnection rate

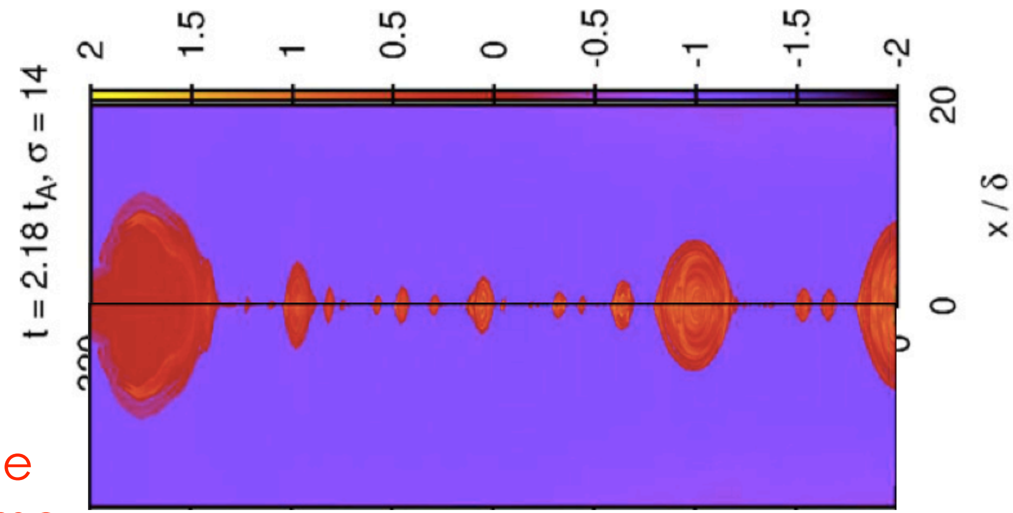




Takahashi+ 2011



Transition to the plasmoid regime



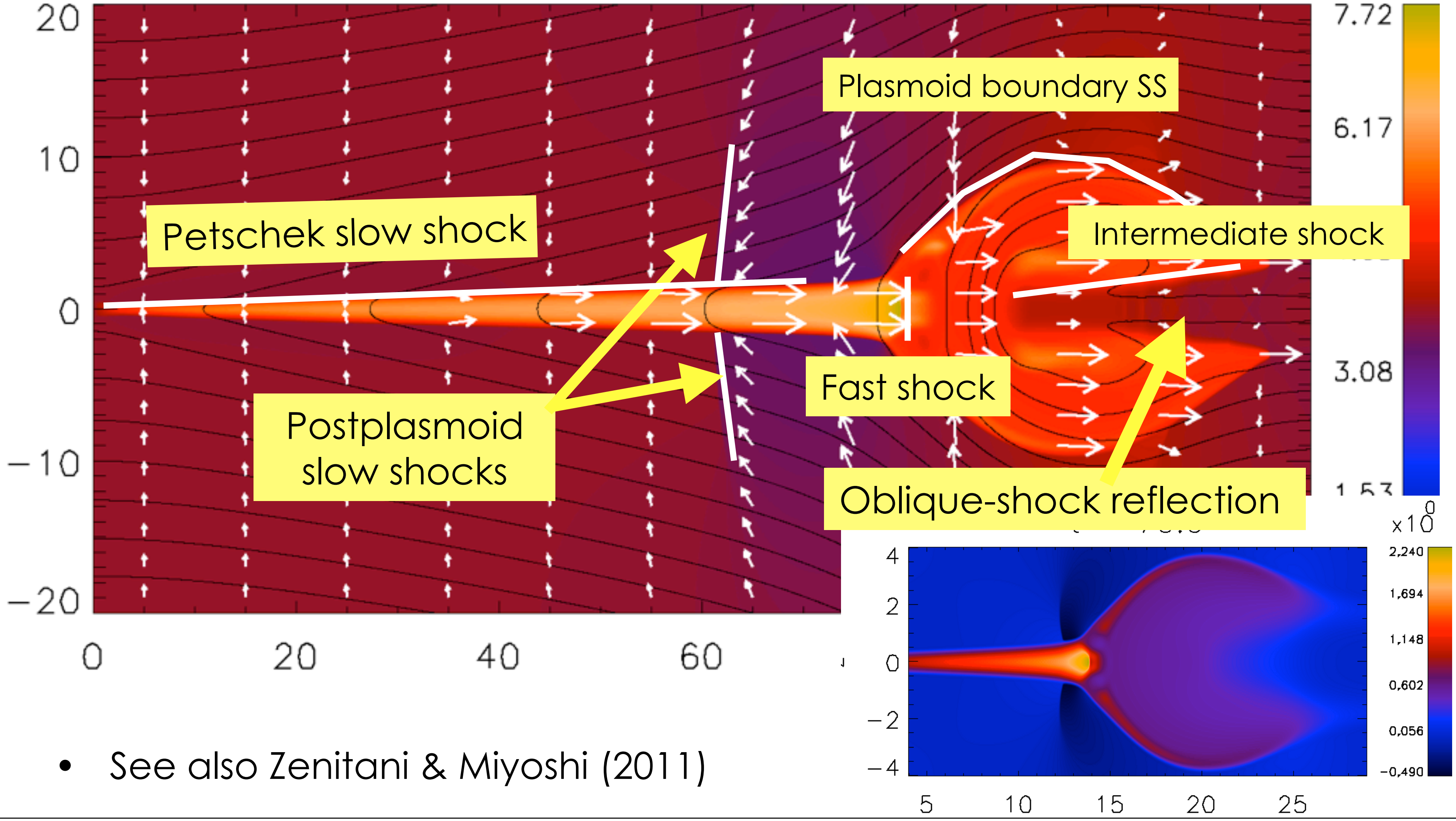
Takamoto 2013

Shock, shock, and shocks...

- Shock-capturing code is essential in the relativistic high-sigma regime

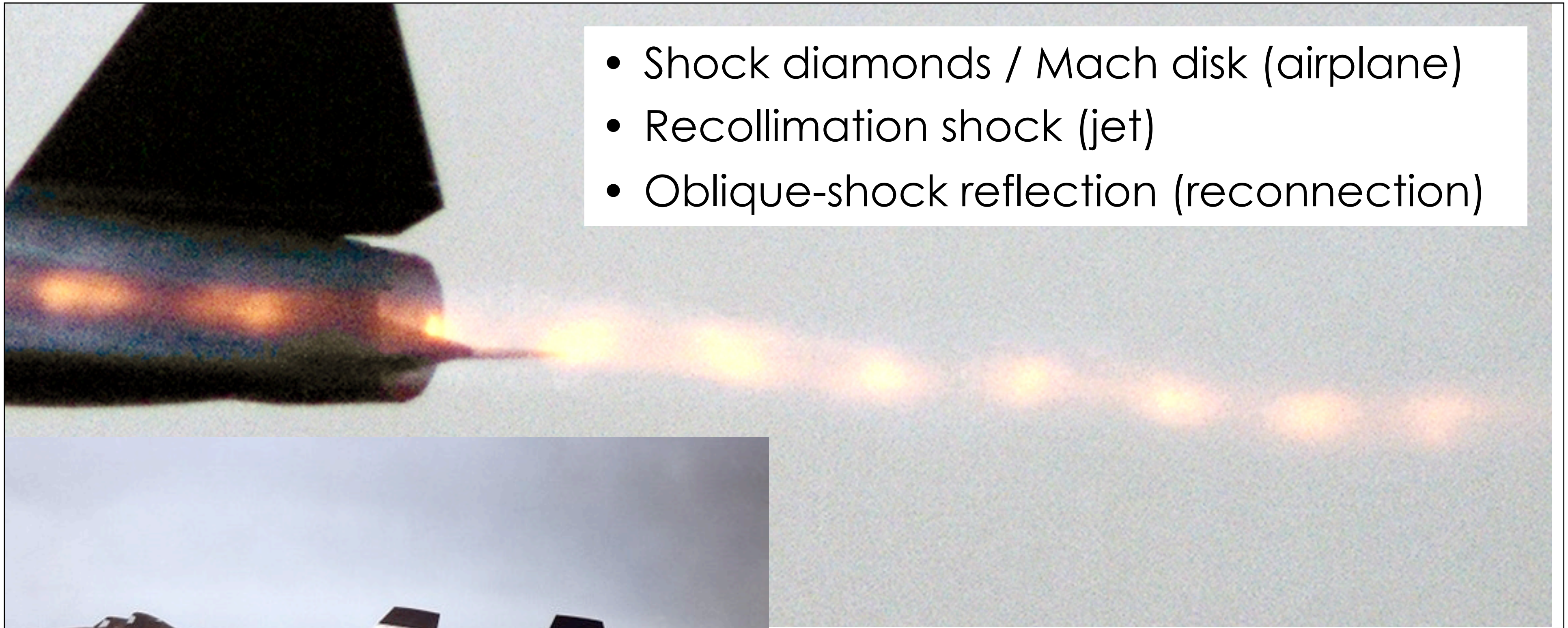
$$\sigma_\varepsilon = \frac{B_0^2}{4\pi\gamma^2 w} \left(\approx \frac{8}{5} \frac{\mathcal{E}_{EM}}{\mathcal{E}_{fluid}} \right) > \frac{1}{2}$$

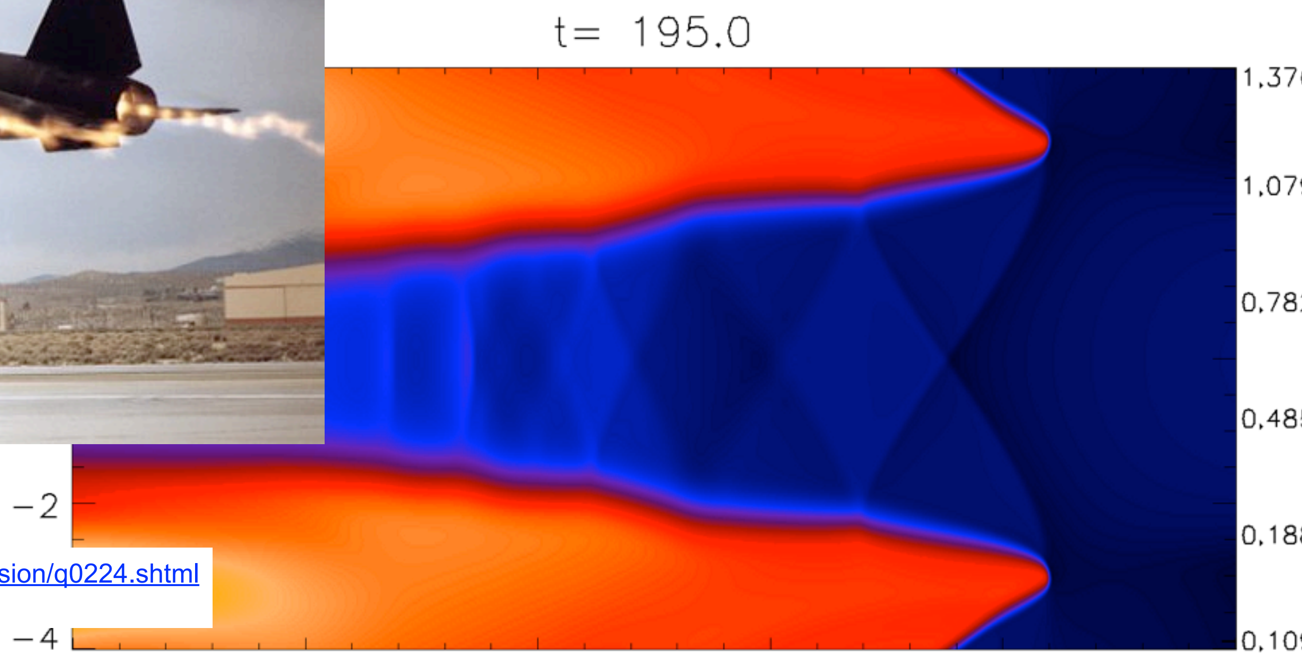
color: $U_x = \gamma V_x$



- See also Zenitani & Miyoshi (2011)

- Shock diamonds / Mach disk (airplane)
- Recollimation shock (jet)
- Oblique-shock reflection (reconnection)





http://www.aerospaceweb.org/question/propulsion/q0224.shtml
http://en.wikipedia.org/wiki/Shock_diamond

Relativistic two-fluid model of pair plasmas

Zenitani+ 2009a,b
Barkov+ 2014

e$^+$-e$^-$ interaction

Continuity (x 2)
$$\frac{\partial D_p}{\partial t} = -\nabla \cdot (n_p \boldsymbol{u}_p)$$

Momentum (x 2)
$$\frac{\partial \boldsymbol{m}_p}{\partial t} = -\nabla \cdot \left(\frac{w_p \boldsymbol{u}_p \boldsymbol{u}_p}{c^2} + \delta_{ij} p_p \right) + \gamma_p n_p q_p \left(\boldsymbol{E} + \frac{\boldsymbol{v}_p}{c} \times \boldsymbol{B} \right) - \tau_{fr} n_p n_e (\boldsymbol{u}_p - \boldsymbol{u}_e)$$

Energy (x 2)
$$\frac{\partial \mathcal{E}_p}{\partial t} = -\nabla \cdot (\gamma_p w_p \boldsymbol{u}_p) + \gamma_p n_p q_p (\boldsymbol{v_p} \cdot \boldsymbol{E}) - \tau_{fr} n_p n_e c^2 (\boldsymbol{\gamma}_p - \boldsymbol{\gamma}_e)$$

Faraday's law
$$\frac{\partial \boldsymbol{B}}{\partial t} = -c \nabla \times \boldsymbol{E}$$

Ampére's law
$$\frac{\partial \boldsymbol{E}}{\partial t} = c \nabla \times \boldsymbol{B} - 4\pi \boldsymbol{j}$$

Out-of-plane Ohm's law

advection / viscous
$$E_y \approx \frac{-\langle v_z \rangle B_x}{c} + \frac{m \langle v_z \rangle}{q_p} \frac{\partial h_p u_{y,p}}{\partial z} + \frac{\eta_{eff}}{\gamma_p} j_y - \frac{m \nu_z}{q_p} \frac{\partial^2 h_p u_{y,p}}{\partial z^2}$$

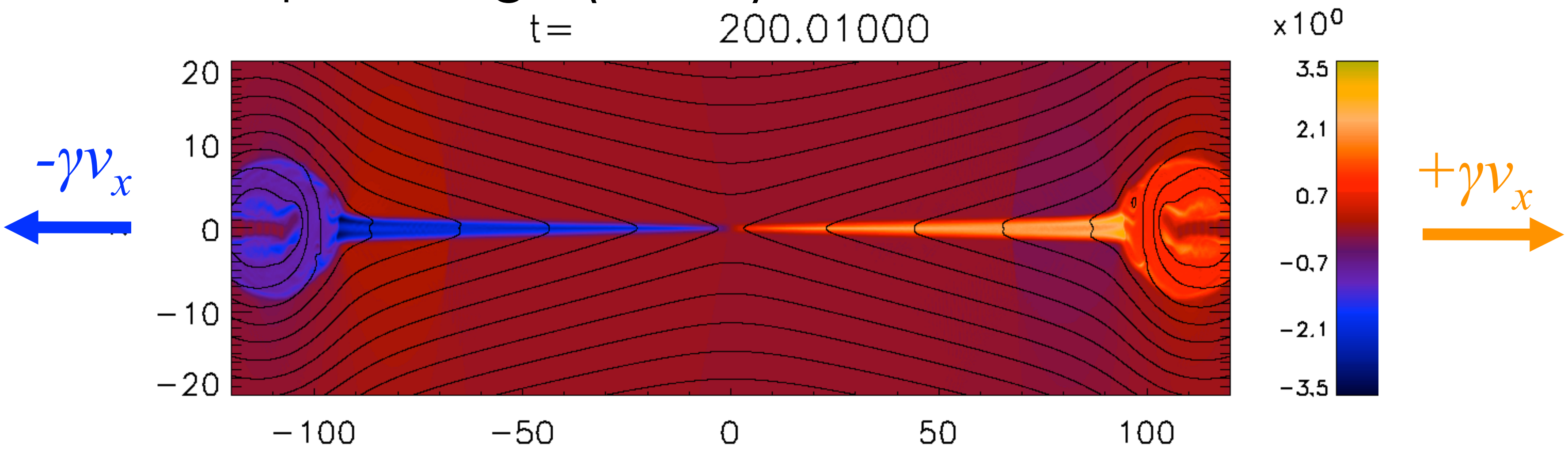
Fluid inertia　Frictional resistivity

four velocity
$$\boldsymbol{u} = \gamma \boldsymbol{v}$$

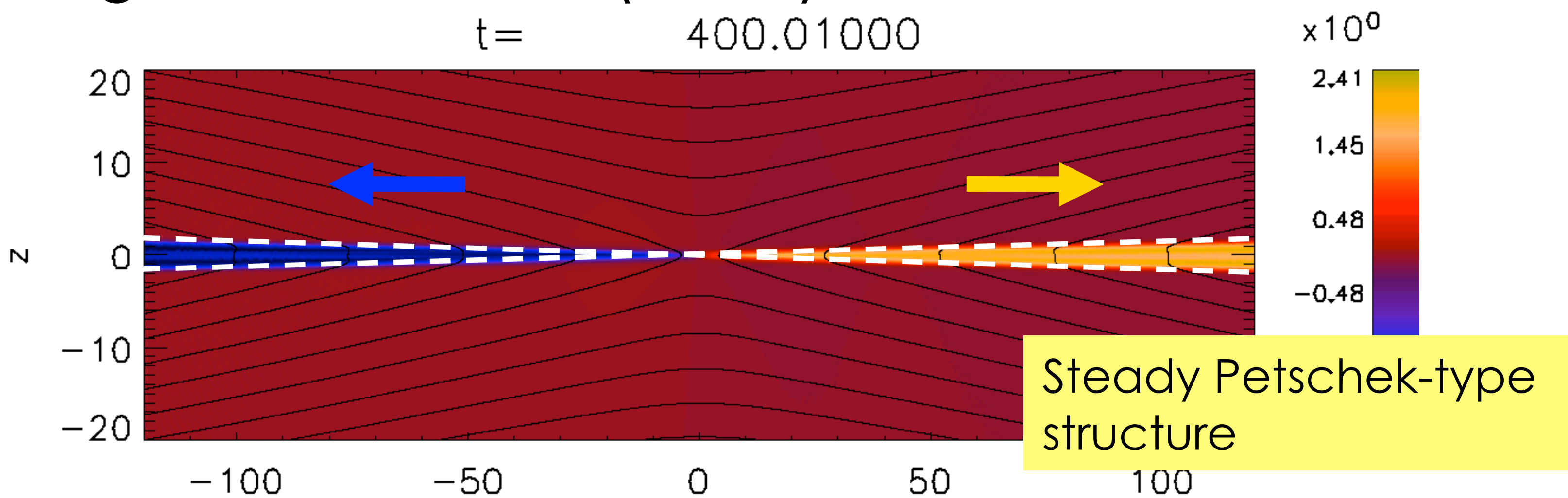
specific enthalpy
$$w_s = e_s + p_s = n_s m c^2 + [\Gamma/(\Gamma - 1)] p_s$$

Large-scale evolution

- Developed stage (t=200)

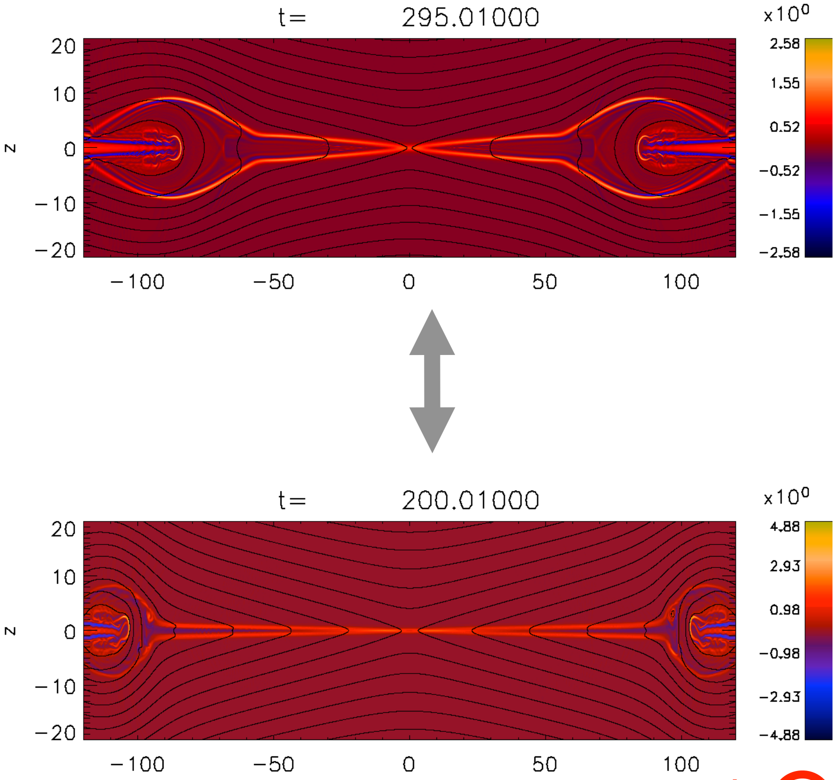


- Long-term evolution (t=400)



Features #1: narrower opening angle

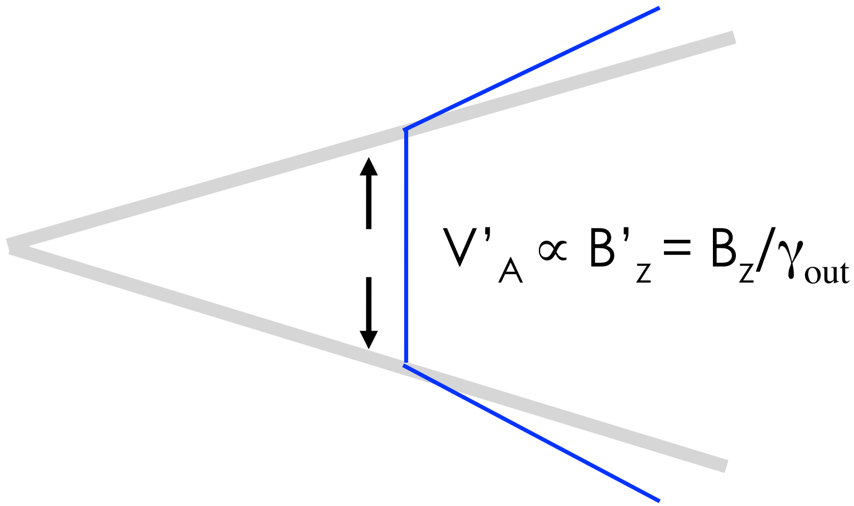
Semi-relativistic (sigma=0.4)



J_y ⊗

Relativistic (sigma=4)

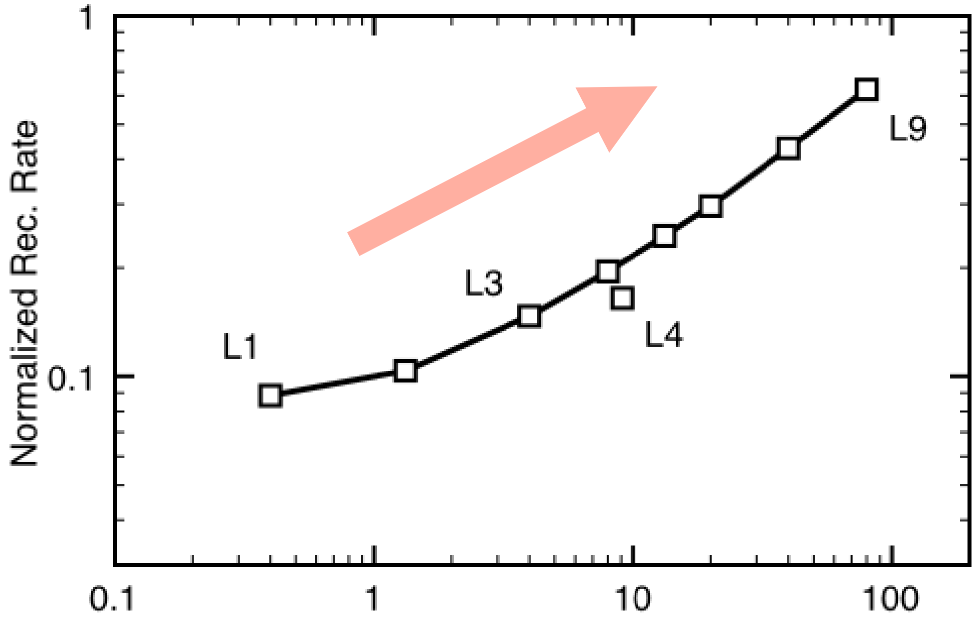
- Opening angle becomes narrower in the ultrarelativistic regime (Lyubarsky 2005)



$$\theta_{rela} \sim \frac{\theta_{nonrela}}{\gamma_{out}^2} \sim \frac{\theta_{nonrela}}{\gamma_A^2}$$

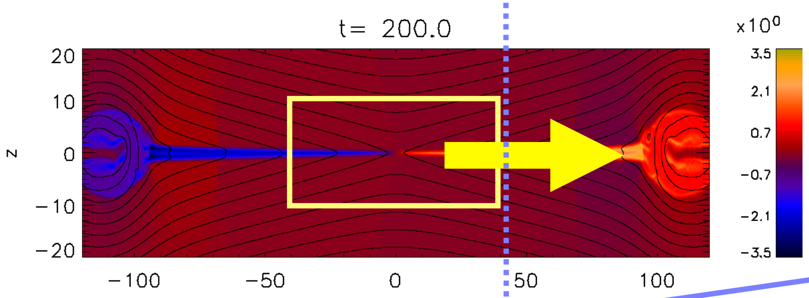
Features #2: faster reconnection speed

- Normalized rate : $$\mathcal{R} = \frac{cE_y}{c_{A,in} B_{x,in}} \approx \frac{v_{in}}{v_{out}}$$

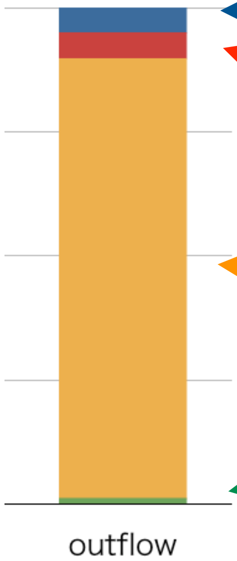


Nonrelativistic ← σ_{ε} → Ultrarelativistic

Features #3: enthalpy-flux dominated outflow



Upstream $\dfrac{B^2}{8\pi}$ ~ outflow p



Matter flow $\gamma n m c^2 \mathbf{v}$ $\left(\leftrightarrow n m c^2 \mathbf{v}\right)$

Bulk kinetic $\gamma(\gamma - 1) n m c^2 \mathbf{v}$ $\left(\leftrightarrow \frac{1}{2} n m v^2 \mathbf{v}\right)$

Enthalpy flux $\gamma^2 \frac{\Gamma}{\Gamma - 1} p \mathbf{v}$ $\left(\leftrightarrow \frac{5}{2} p \mathbf{v}\right)$

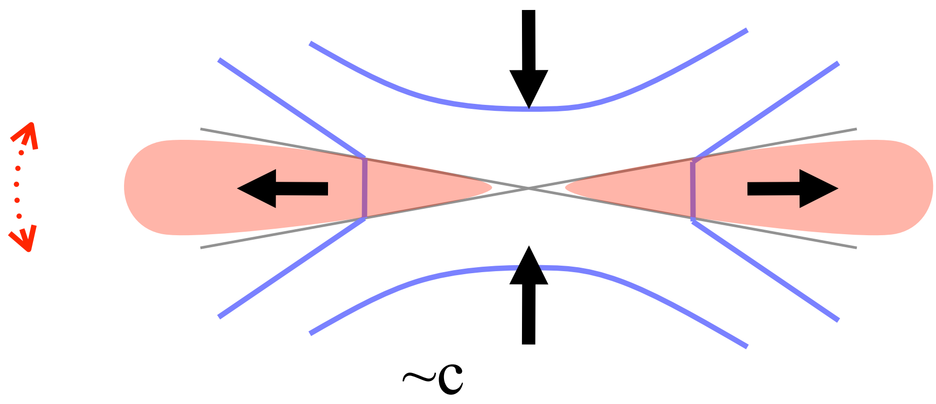
Poynting flux $\frac{c}{4\pi}(\mathbf{E} \times \mathbf{B})$

- Enthalpy flux (~ internal energy flux) carries outgoing energy
- Plasma pressure balances with the strong upstream magnetic pressure

Relativistic features of PK reconnection

- #1 Narrower opening angle
- #2 Faster reconnection rate R ~ 0.1-1
- #3 Enthalpy-flux dominated outflow

- Relativistic enthalpy flux (~internal energy flux) allows larger energy output per cross section

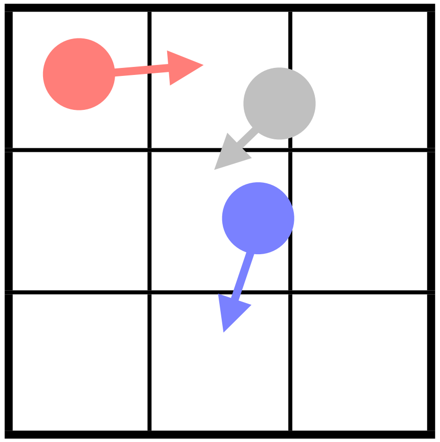


$$\gamma^2 \frac{\Gamma}{\Gamma - 1} p \mathbf{v}$$

2. Kinetic simulations

Kinetic model: Particle-In-Cell simulation

particle quantities : q, **x, v**



cell properties : **J**, ρ , **E, B**

- $10^1 \sim 10^3$ virtual particles in a cell
  - 1. Solve particle motion

$$\frac{d}{dt}(m_j \gamma_j \boldsymbol{v}_j) = q_j\left(\boldsymbol{E} + \frac{\boldsymbol{v}_j}{c} \times \boldsymbol{B}\right)$$

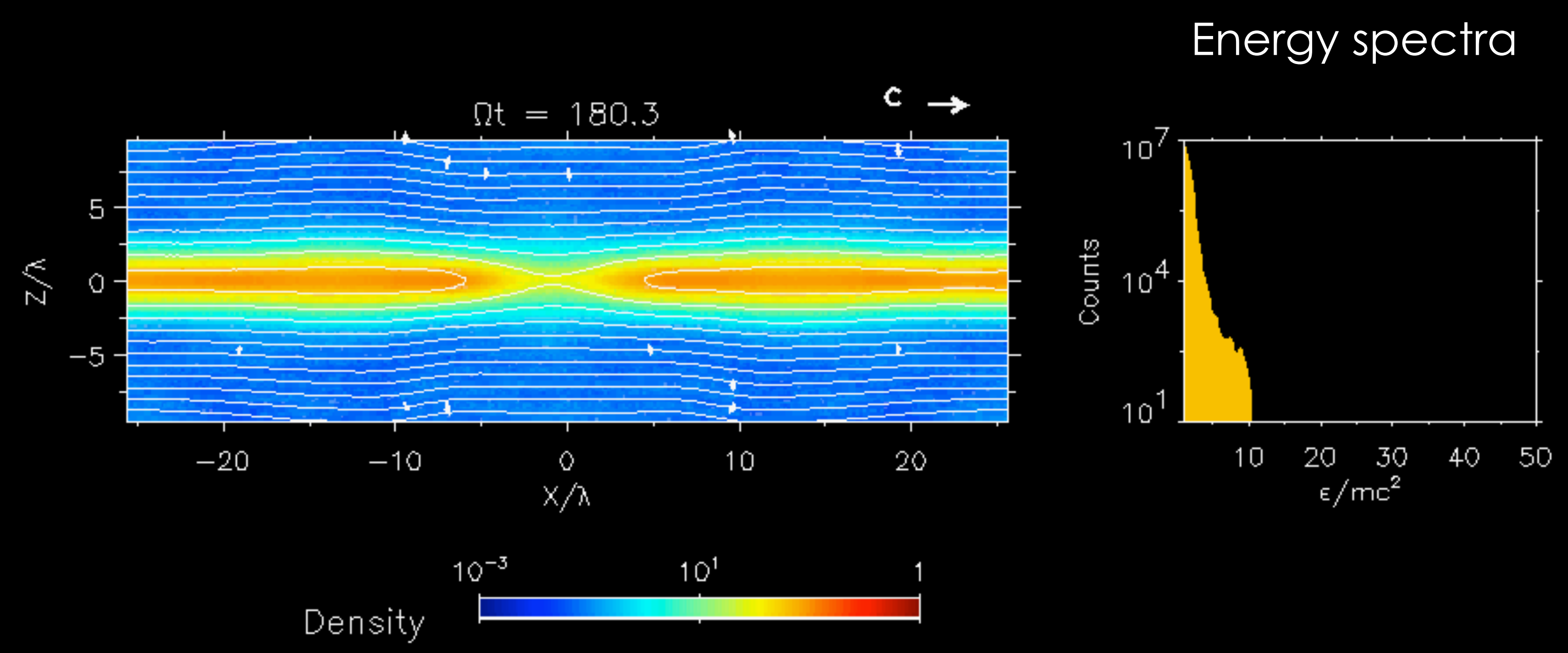
$$\frac{d}{dt}\boldsymbol{x}_j = \boldsymbol{v}_j,$$

  - 2. Update J, ρ
  - 3. Advance EM field (E, B)

- Huge computational cost
- Detail plasma physics
  - particle acceleration
  - anisotropic distribution function

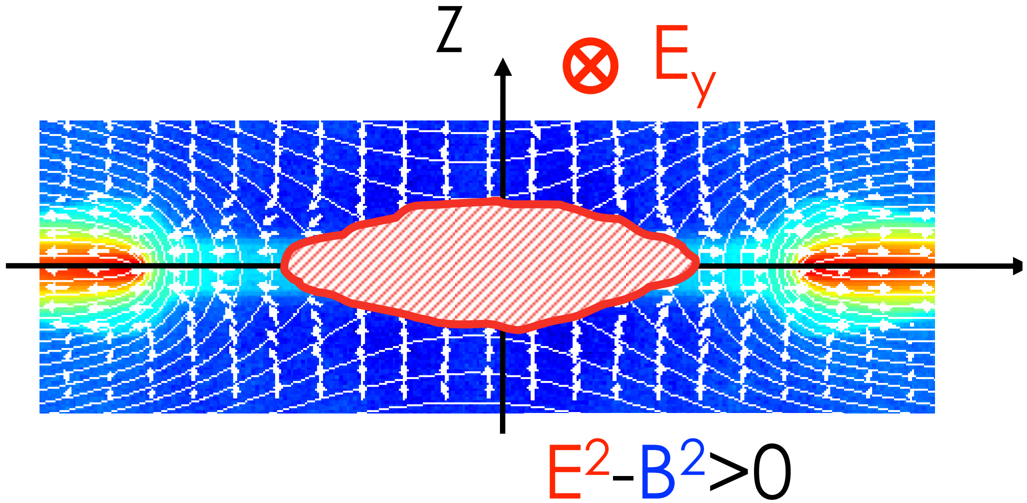
2D Particle-In-Cell (PIC) simulation

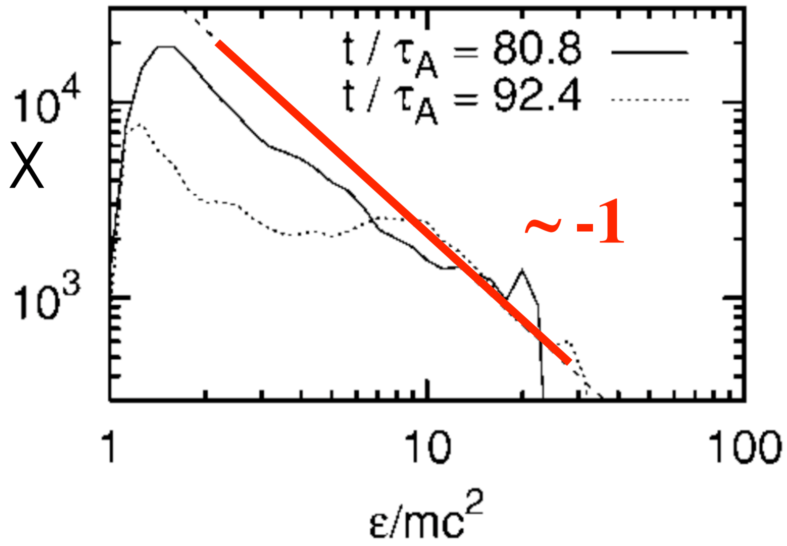
- Fast reconnection and particle acceleration occurs
- Online version: http://th.nao.ac.jp/MEMBER/zenitani/files/reconnection.mov



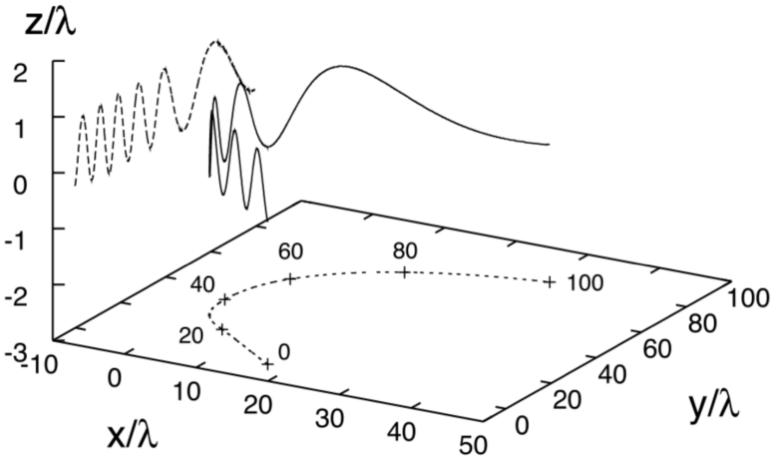
Zenitani & Hoshino 2001, 2007

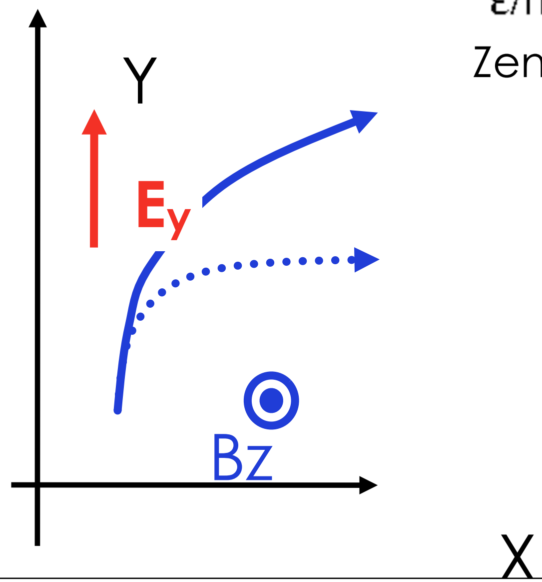
DC particle acceleration via relativistic Speiser motion





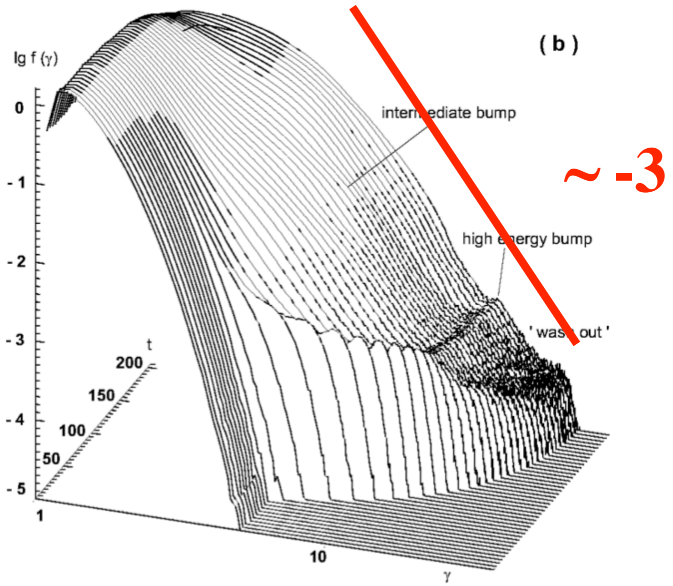
Zenitani & Hoshino 2001



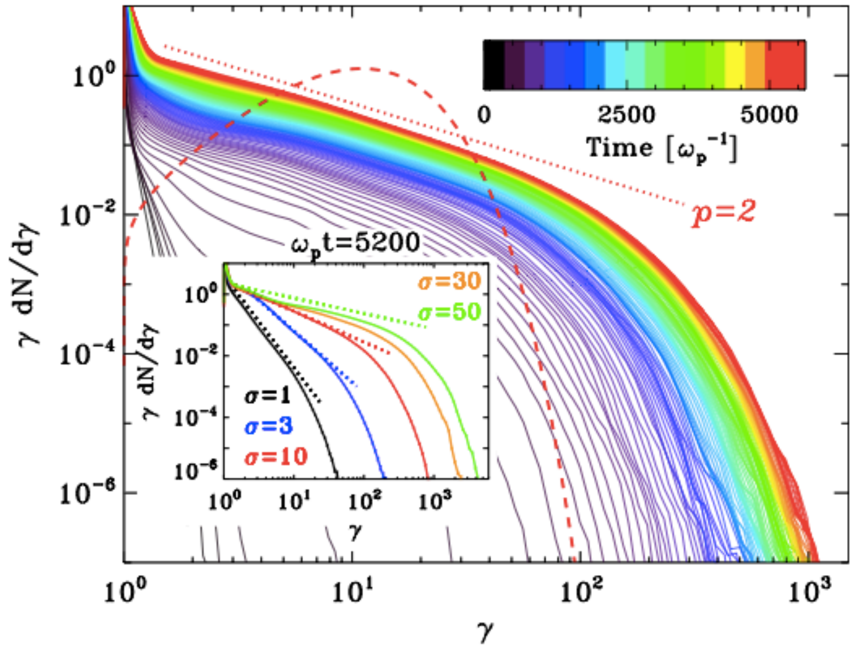


Zenitani & Hoshino 2007

Large-scale dynamic evolution



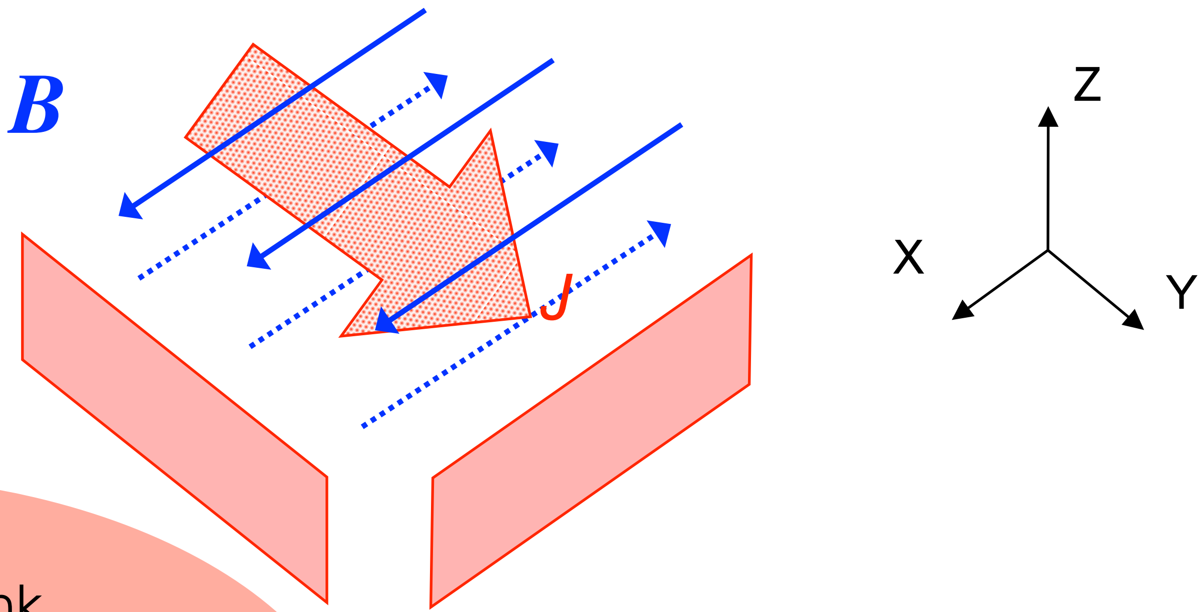
Jaroschek et al. 2004



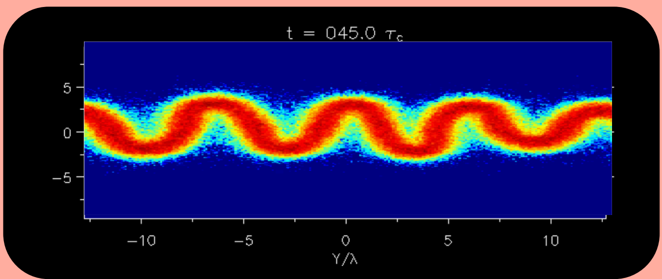
Sironi & Spitkovsky 2014

- Power-law index
  s ~ -1 (near acc. region), -2.4~3 (global)
- Hard emission spectra (Jaroschek+ 2004, Cerutti+ 2012)

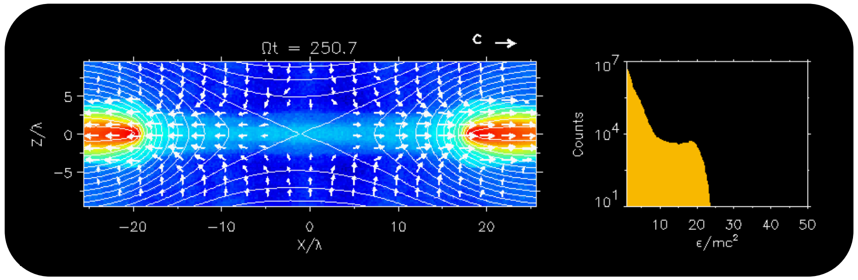
Another 2D problem:
Drift-Kink Instability (DKI)



Relativistic drift kink instability (DKI)

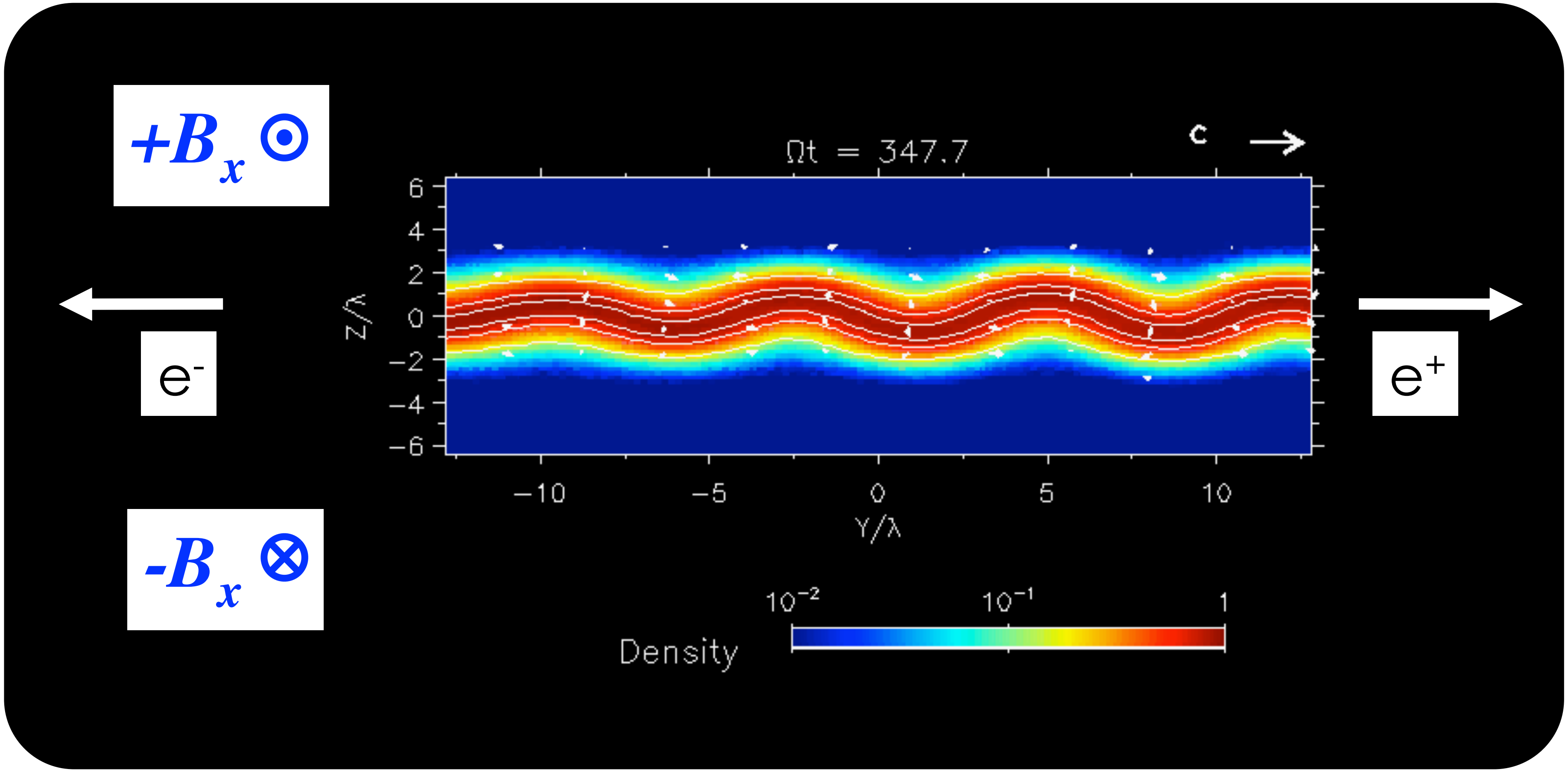


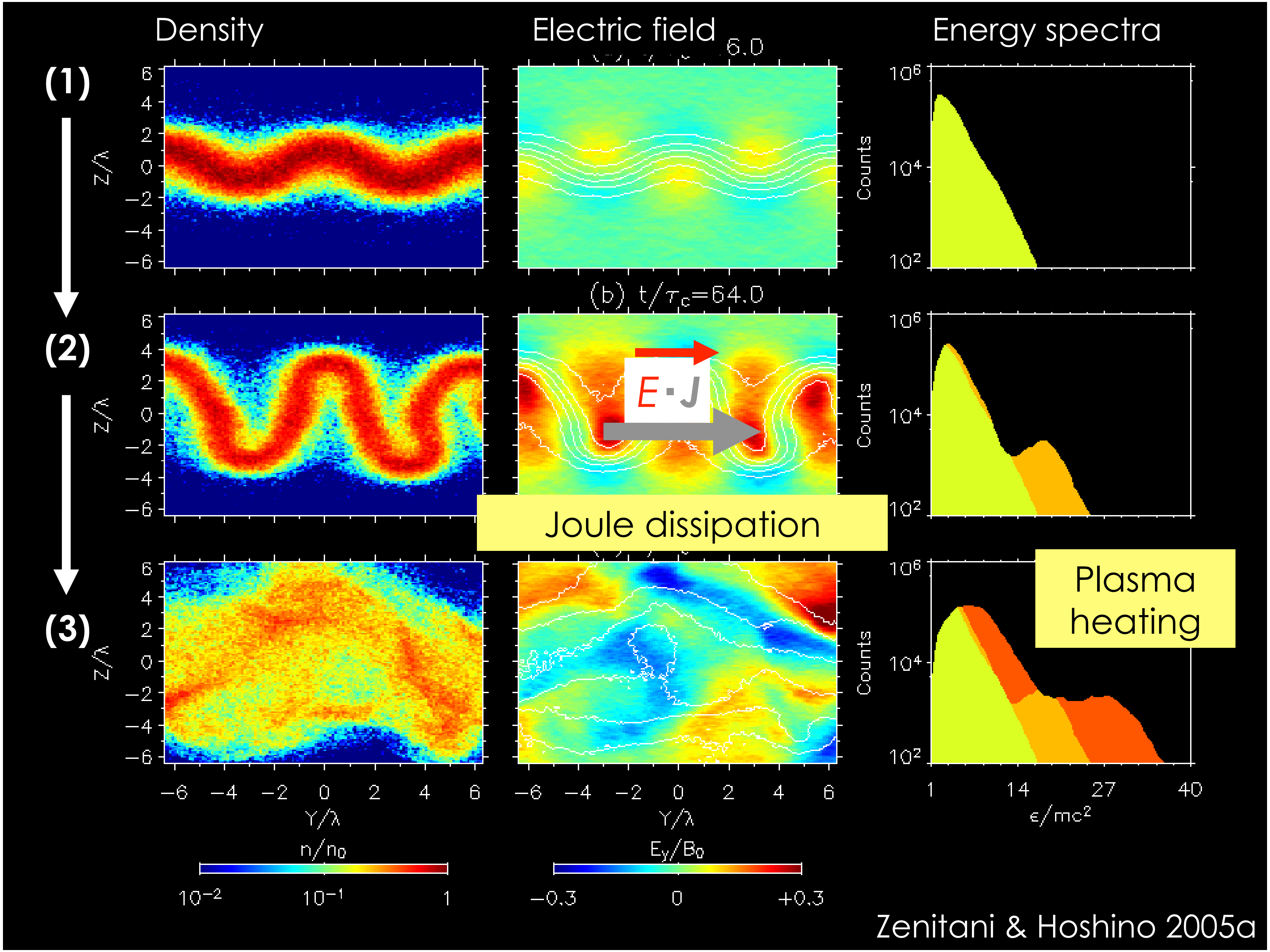
Magnetic reconnection (RX)



Relativistic Drift-Kink Instability

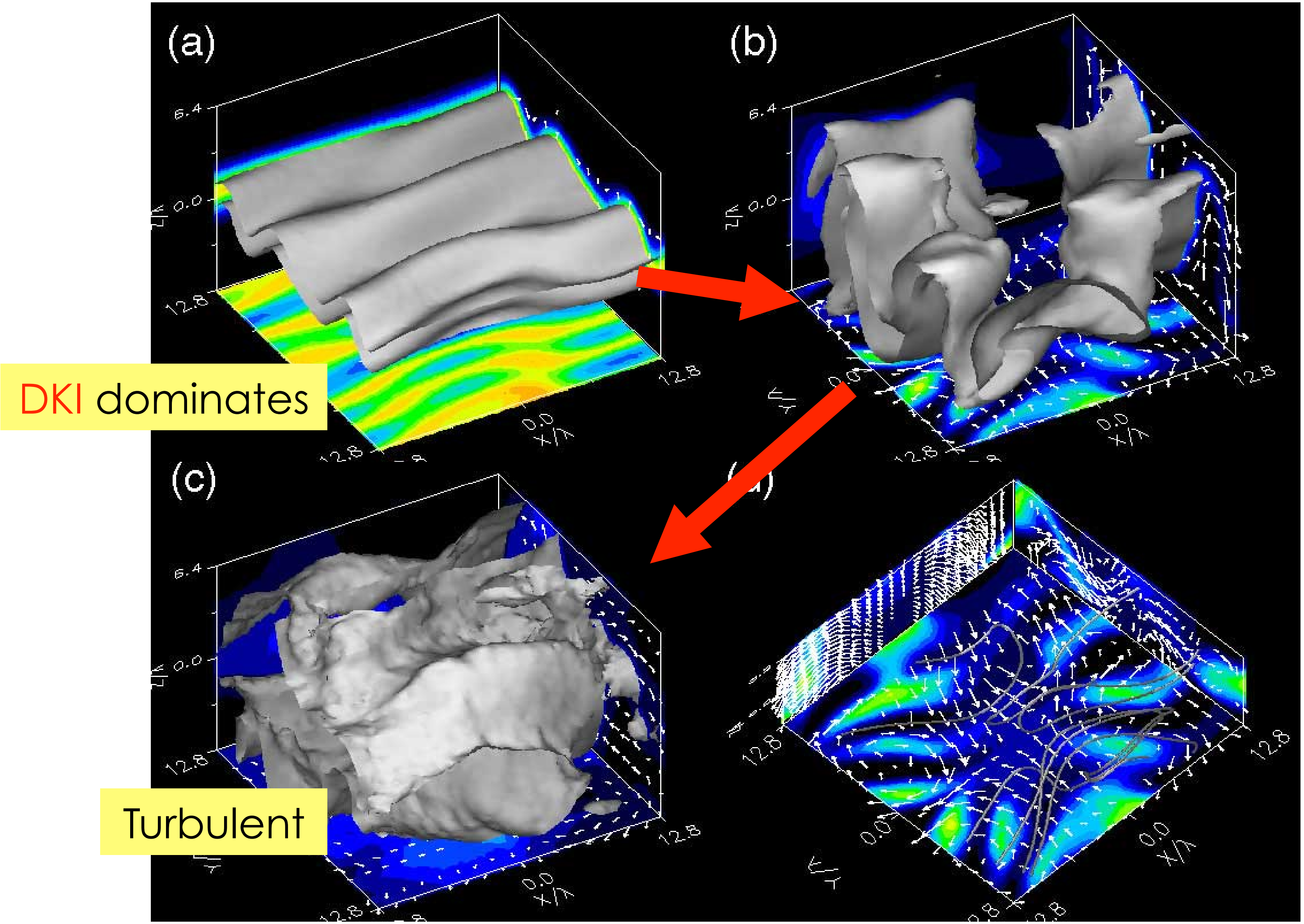
- A kink-type instability, driven by the electron-positron counter-stream (Zhu & Winglee 1996, Ozaki+ 1996, Pritchett+ 1996)
- Online version: http://th.nao.ac.jp/MEMBER/zenitani/files/RDKI.mov





Density
Electric field
Energy spectra
(1)
(2)
(3)
(b) t/τc=64.0
E·J
Joule dissipation
Plasma heating
Z/λ
Y/λ
n/n0
10^-2
10^-1
1
Ey/B0
−0.3
0
+0.3
Counts
ε/mc²
1
14
27
40
Zenitani & Hoshino 2005a

3D evolution

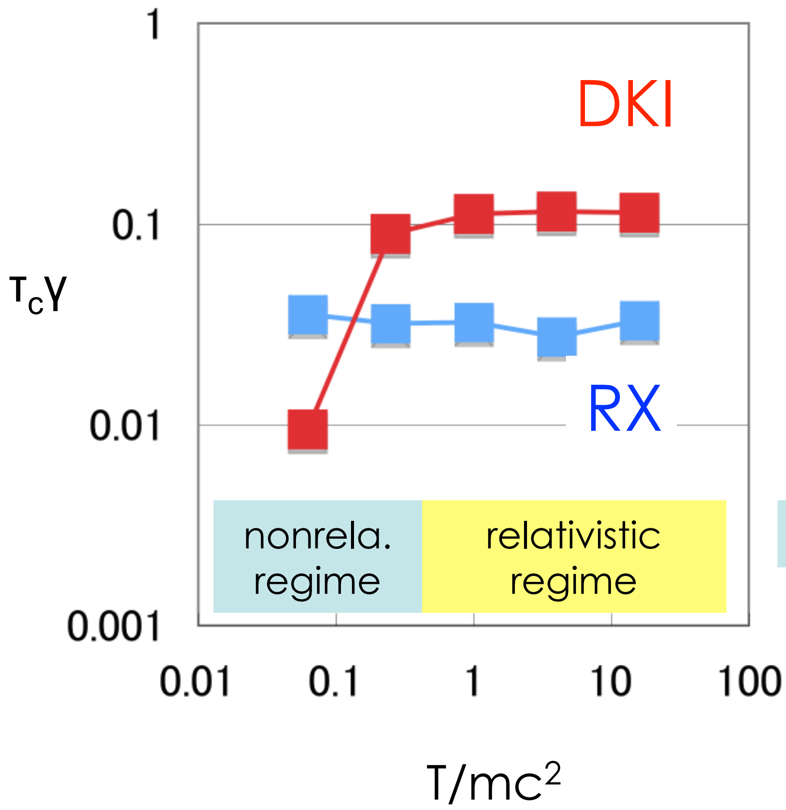


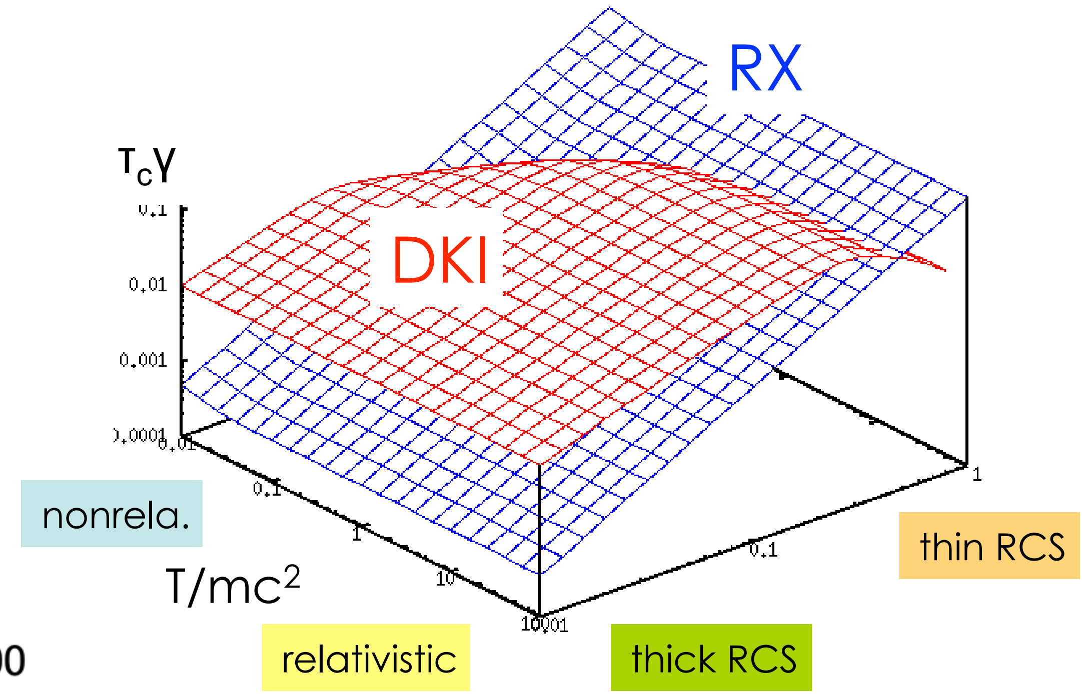
Zenitani & Hoshino 2008

Growth rates of the competing modes

RX (tearing; acceleration) vs DKI (plasma heating).
In the relativistic regime, DKI grows faster.

- PIC simulation
- Theoretical estimate

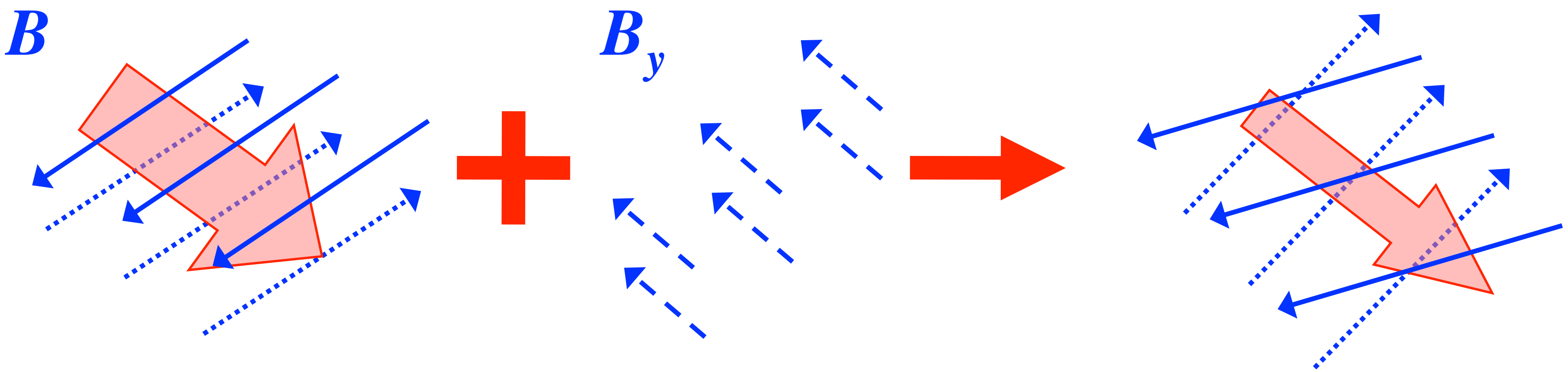




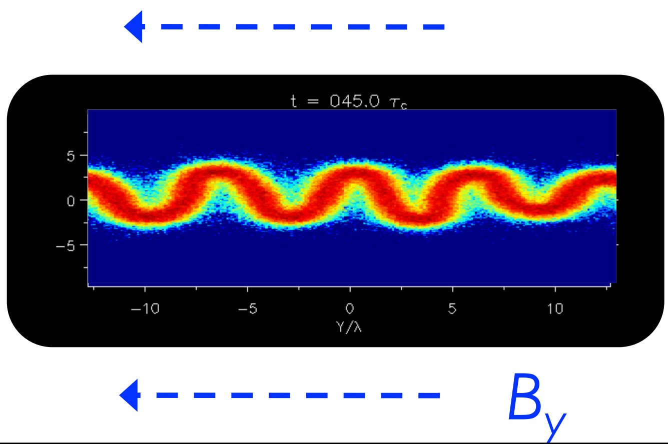
Zenitani & Hoshino 2007

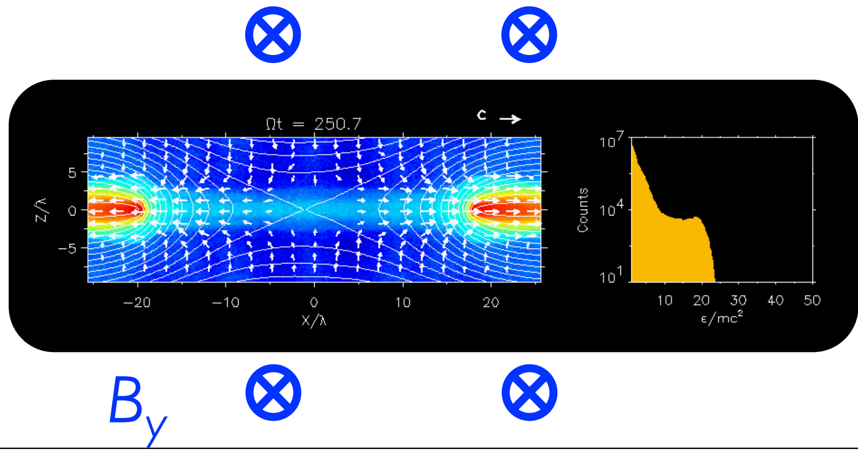
Field topology effect -- a guide field

- Antiparallel field + Uniform guide field B_y

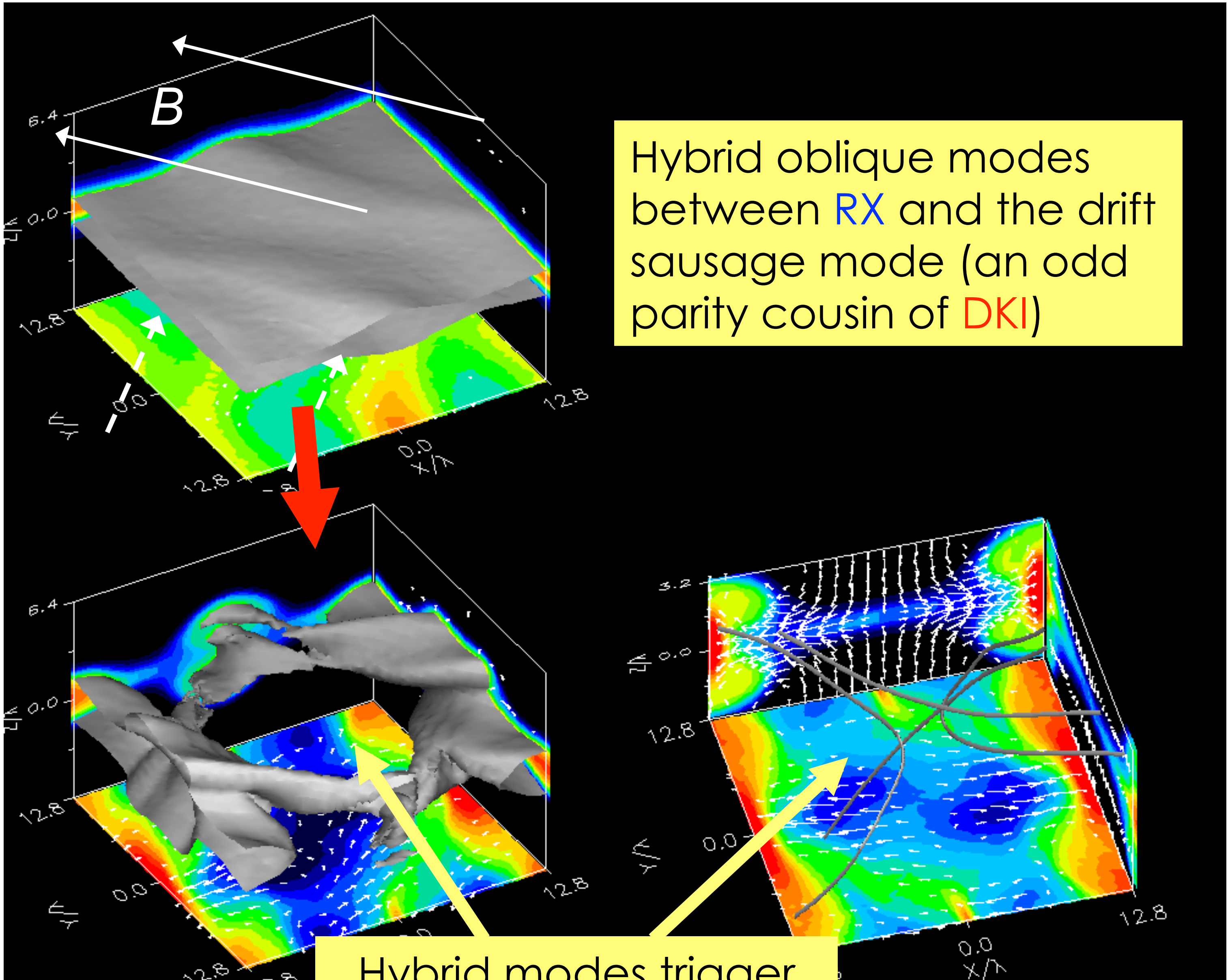


- Magnetic tension stabilizes DKI
- RX is relatively insensitive





3D evolution with guide field

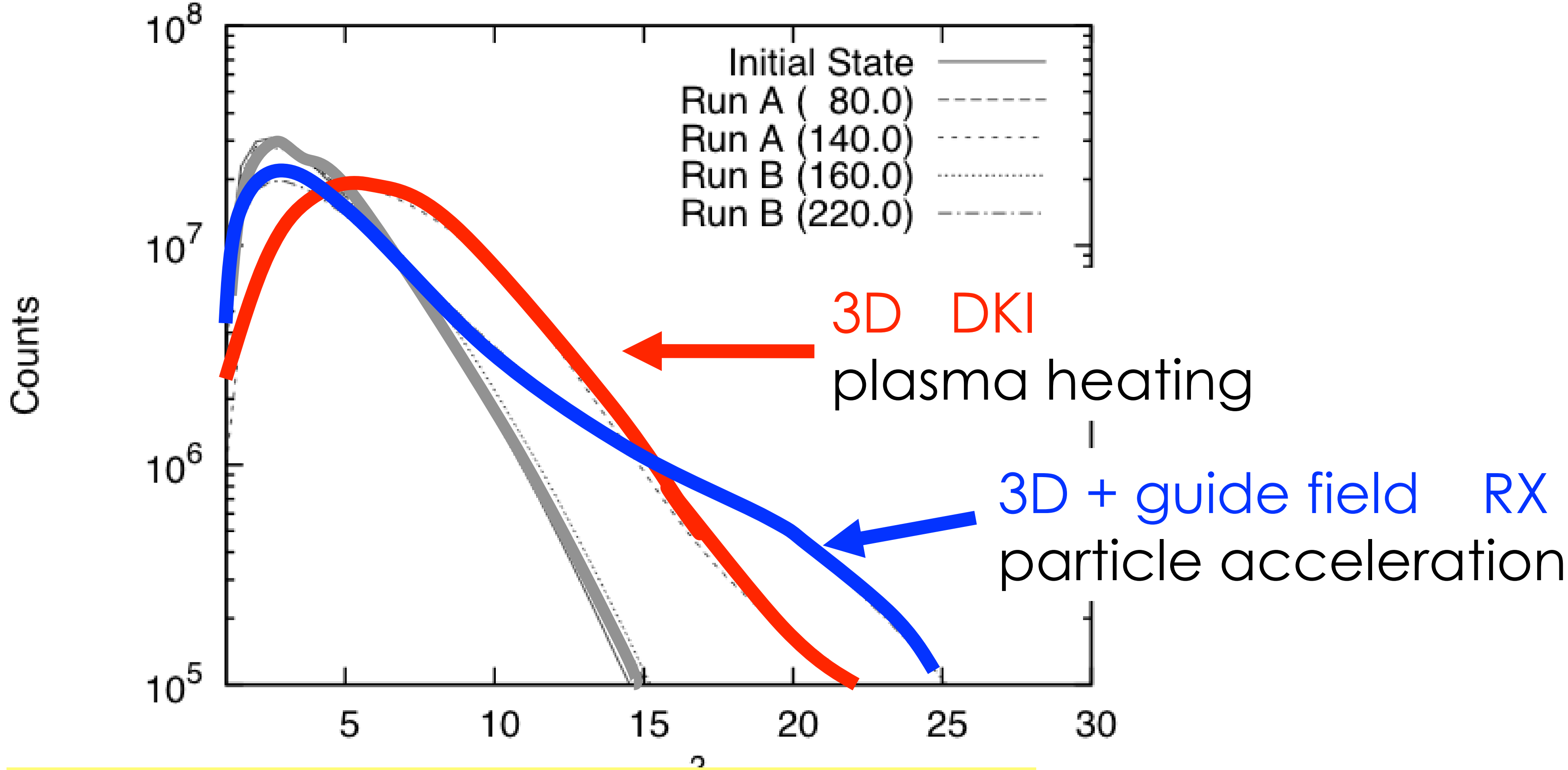


Hybrid oblique modes between RX and the drift sausage mode (an odd parity cousin of DKI)

Hybrid modes trigger secondary RX

Zenitani & Hoshino 2005 PRL

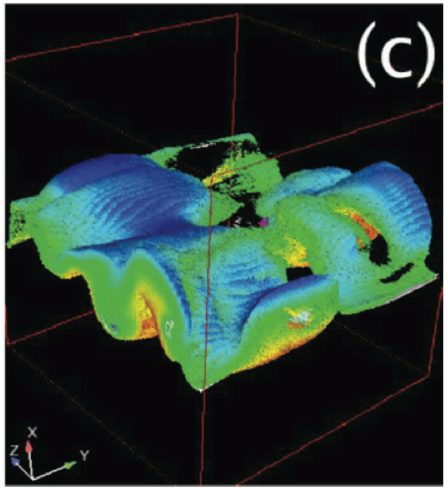
Energy spectra in 3D simulations



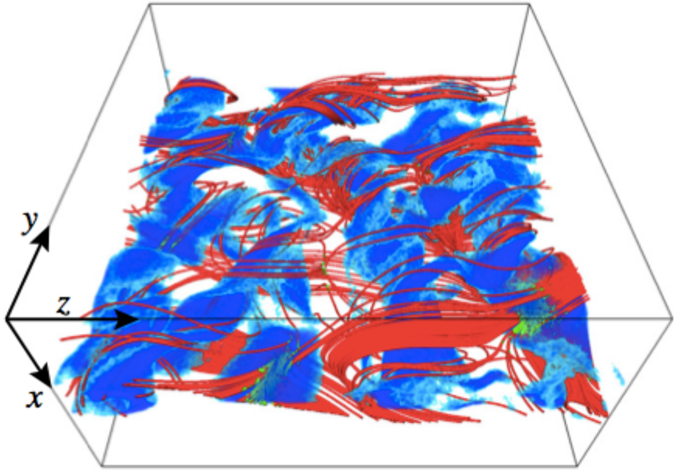
Magnetic topology changes
the destination of released energy!
Plasma heat vs non-thermal energy.

Zenitani & Hoshino 2005 PRL

3D evolution: mode competition



Liu+ 2011



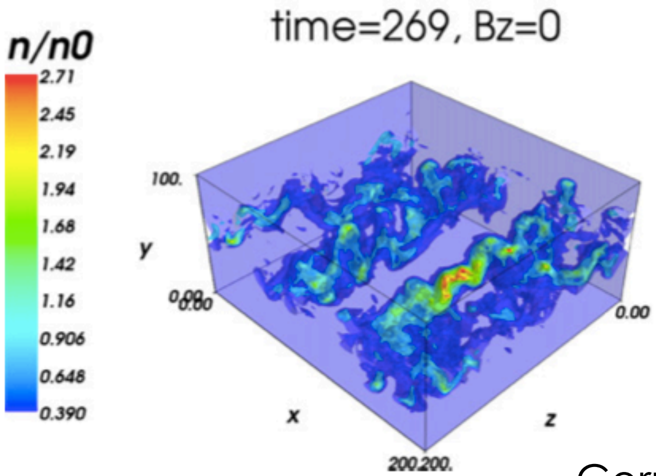
Kagan+ 2013

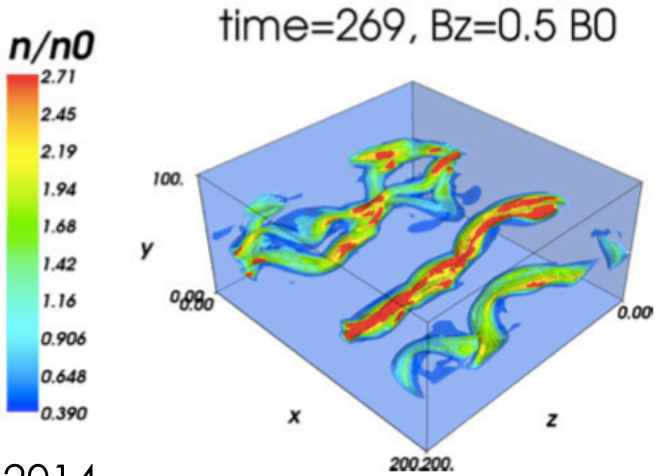
Anti-parallel

plasma heating

Guid-field RX

particle acceleration

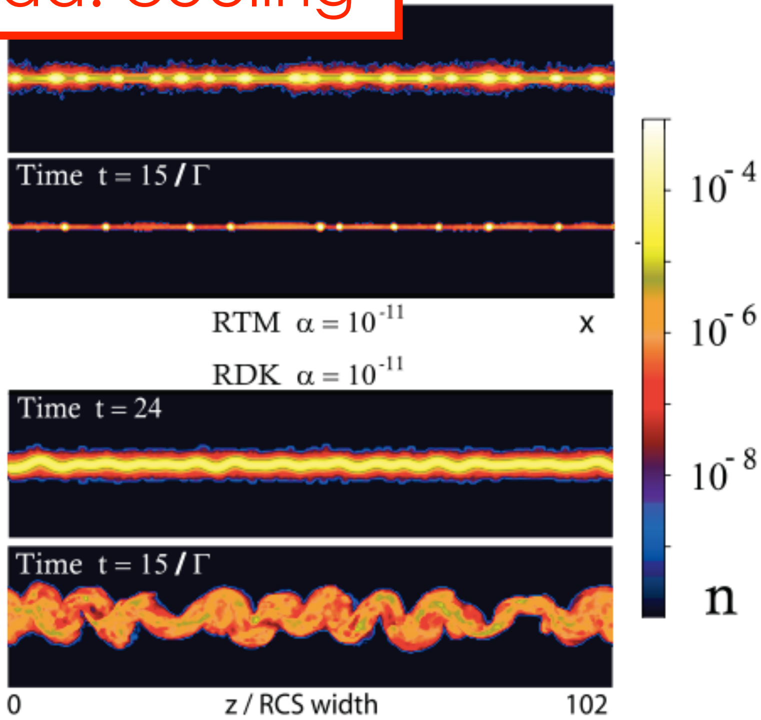




Cerutti+ 2014

New frontiers: radiation & GR

Kinetic with rad. cooling

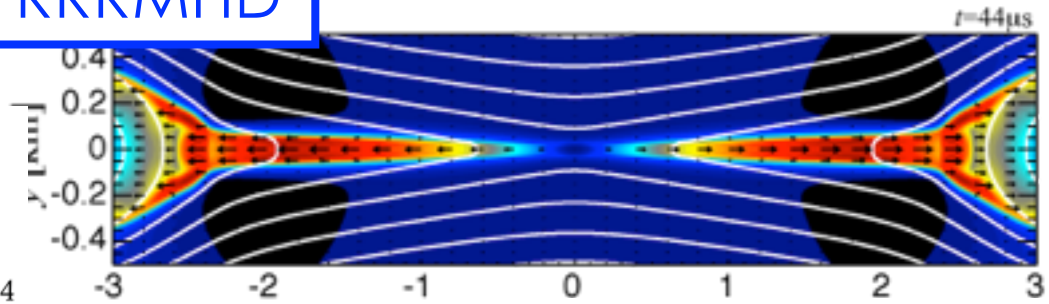


Jaroschek & Hoshino 2009

Cerutti+ 2013, 2014

Tamburini+ 2010

RRRMHD



Takahashi & Ohsuga 2013

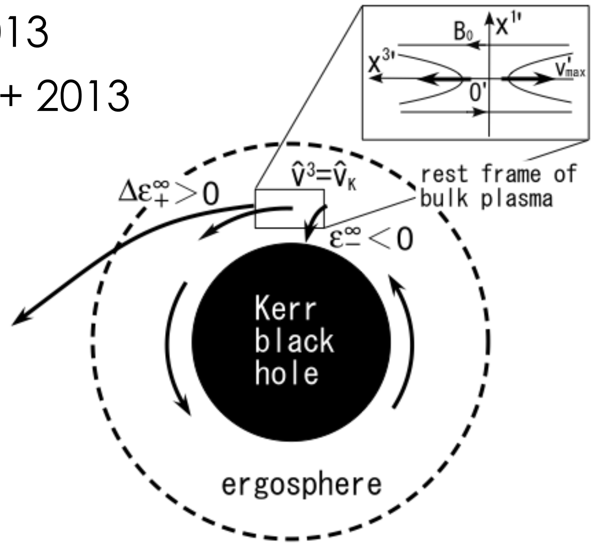
GRRMHD

Bucciantini & Del Zanna 2013

Palenzuela+ 2013

Dionysopoulou+ 2013

Koide+ 201X

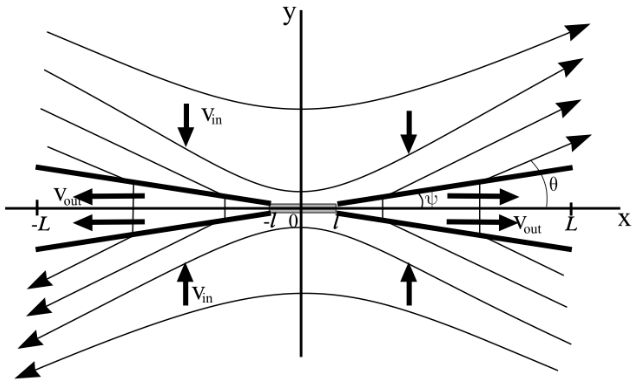


Summary

- RRMHD, Two-fluid picture
  - Straightforward extension of nonrelativistic MHD reconnection
  - Some differences
    - Narrower exhaust, faster reconnection rate, heat-dominated flow
  - Various shocks!
- Kinetic picture
  - Reconnection (RX) - DC particle acceleration
  - Drift Kink instability (DKI) - plasma heating
  - 3D evolution - mode competition RX vs DKI
    - Guide field changes the winner
  - Weibel instability (WBI) - yet another player
- Forefronts
  - Large-scale 3D kinetic evolution
  - Radiation effect
  - GRRMHD: application to BH

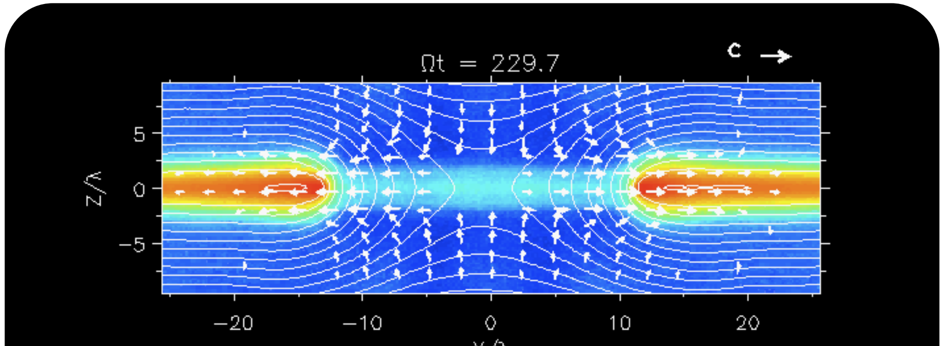
Reconnection gallery

MHD theory



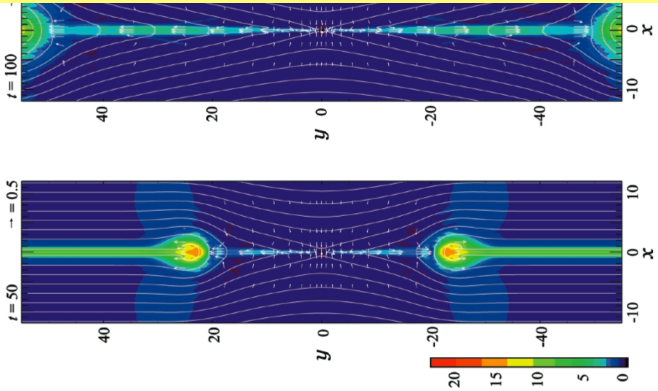
Lyubarsky 2005

Kinetic simulations



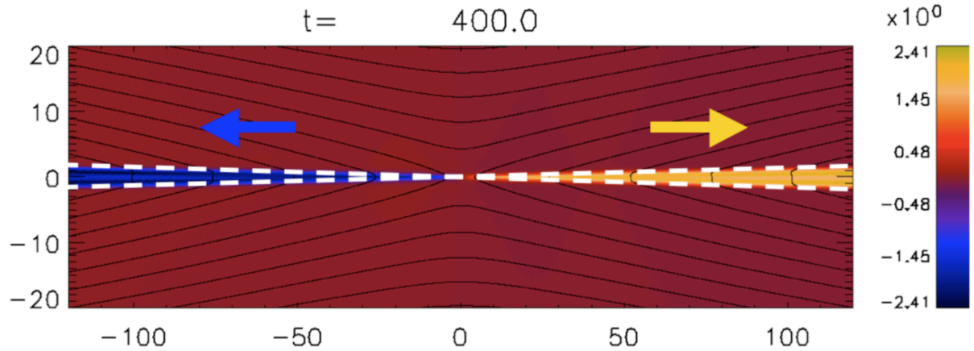
Zenitani & Hoshino 2007

Successful launch in the 1st decade (2001-2010)
A lot more to come in the 2nd decade (2011~)



Watanabe & Yokoyama 2006

RRMHD simulations



Zenitani+ 2009a

Two-fluid simulations